SUSTAINABLE IMPACT EVALUATION OF ENERGY RETROFITS FOR SCHOOL BUILDINGS IN DIFFERENT CLIMATE REGIONS

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ABSTRACT

SUSTAINABLE IMPACT EVALUATION OF ENERGY RETROFITS FOR SCHOOL BUILDINGS IN DIFFERENT CLIMATE REGIONS

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Due to increasing importance of the concepts of energy efficiency and sustainability, retrofits for a large portion of existing buildings have become an immediate necessity. In this respect, different retrofit strategies are employed for increasing the efficiency of existing building envelopes, energy sources, electrical and mechanical systems.

Among the existing building types for efficiency retrofit are the school buildings, which differ from the rest due to their special function - education. The activities taking place in the schools require well established environmental conditions for effectiveness. In Turkey, a large number of high school and elementary school buildings (a total of about 66000 units) have been constructed by repeating a prototype design project to decrease costs and increase speed. Due to the variance of climatic conditions across the country, these buildings have varying environmental performance. Therefore, retrofit of existing school buildings in Turkey has become a necessity and the retrofit strategies that will be produced for these buildings are very important for future generations.

The aim of this study is to evaluate the effect of different energy retrofit measures on the sustainability of the schools in different climatic zones. In other words, it is aimed to emphasize that the energy retrofits to be implemented to prototype school projects does not have the same economic, environmental, and social sustainability impacts across different climatic regions.

In this study, for the evaluation of four prototype school building in different climate regions and four different retrofit measures, 16 cases were generated. The impact of each case on environmental, economic and social sustainability was evaluated and the sustainability impacts of 16 different cases were calculated as the sum of these three values. As a result of all calculations, a three-dimensional matrix was created to demonstrate the impact of different retrofit types on sustainability in different climatic regions.

Keywords: Sustainability Impact, Sustainability in School Buildings, Energy Retrofit Measures, Climate-Based Retrofit Measures

ÖZ

FARKLI İKLİM BÖLGELERİNDEKİ OKUL BİNALARINA YAPILAN ENERJİ İYİLEŞTİRME ÇALIŞMALARININ SÜRDÜREBİLİRLİK ETKİSİNİN DEĞERLENDİRİLMESİ

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Günümüzde önemi giderek artan enerji verimliliği ve sürdürebilirlik kavramları ile, tadilat ve iyileştirme çalışmaları mevcut yapılar için bir ihtiyaç haline gelmiştir. Bu bağlamda, mevcut yapıların bina kabuğu, enerji kaynakları, elektrik ve mekanik sistemleri ile ilgili farklı tadilat ve iyileştirme stratejileri uygulanmaktadır.

Mevcut yapı tiplerinden biri de yapı özel fonksiyonu, eğitim, gereği diğer mevcut yapı tiplerinden ayrılan okul yapılarıdır. Okul yapılarındaki kullanıcıların verimliliği sağlamak için iyi düzeyde çevresel koşulların sağlanması gerekmektedir. Türkiye'de yaklaşık olarak 66000 adet olduğu bilinen ilkokul ve lise yapılarının bir özelliği de hızlı ve düşük maliyetli yapı üretmenin bir yöntemi olan tip proje yöntemi ile ülkenin dört bir tarafında üretilmiş olmalarıdır. Fakat, ülke genelindeki iklim koşullarının farklılığından dolayı, bu binalar değişken çevresel performansa sahiptir. Ayrıca, tadilat ve iyileştirme çalışmaları Türkiye'deki mevcut okul yapıları için bir gerekliliktir ve bu okul yapıları için geliştirilecek olan stratejiler gelecek nesiller için de büyük önem taşımaktadır.

Bu çalışmada amaç farklı iklim bölgelerindeki tip okul yapılarında önerilebilecek olan yenileme ve tadilat çalışmalarının sürdürebilirlik üzerindeki etkisinin

değerlendirilmesidir. Başka bir deyişle, bu çalışmada farklı iklim bölgelerindeki tip okul projelerine uygulanan aynı tadilat ve iyileştirme çalışmalarının ekonomik, ekolojik ve sosyal sürdürebilirliği aynı şekilde etkilemeyeceğini vurgulamak amaçlanmıştır.

Bu çalışmada, farklı iklim bölgelerindeki dört tip okul projesinin ve dört farklı tadilat yenileme çalışmasının değerlendirilmesi için on altı farklı durum oluşturulmuştur. Her bir durumun ekolojik, ekonomik ve sosyal sürdürebilirliğe olan etkisi değerlendirilmiş ve bu üç değerin toplamı olarak 16 farklı durumun sürdürebilirlik etkisi hesaplanmıştır. Tüm hesaplamalar sonucunda, farklı iklim bölgelerindeki farklı yenileme çalışmalarının sürdürebilirlik üzerindeki etkisini ortaya koyan üç boyutlu bir matris oluşturulmuştur.

Anahtar Kelimeler: Sürdürebilirlik Etkisi, Okul Yapılarında Sürdürebilirlik, Enerji İyileştirme Çalışmaları, İklim Bazlı Enerji İyilştirme Çalışmaları

To my family

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LIST OF ABBREVIATIONS

ASHP	Air Source Heat Pump
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCR	Benefit-Cost Ratio
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
DOE	Department of Energy
DPP	Discounted Payback Period
ERV	Energy Recovery Ventilation
ETICS	External Thermal Insulation Composite System
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
HRV	Heat Recovery Ventilation
HVAC	Heating Ventilation Air Conditioning
IRR	Internal Rate of Return
ISO	International Organization for Standardization
LCA	Life-Cycle Analysis
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Analysis
LED	Light-Emitting Diode

LEED	Leadership in Energy and Environmental Design
NPV	Net Present Value
OLED	Organic Light Emitting Diode
ORR	Overall Rate of Return
PAY	Payback period
PCM	Phase Change Material
PET	Poly Ethylene Terephthalate
PV	Photovoltaic
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SAGSHIPS	Solar-Assisted Ground Source Heat Pump Systems
SIA	Social Impact Assessment
SSTES	Seasonal Solar Thermal Energy Storage
STE	Solar Thermal Energy

CHAPTER 1

INTRODUCTION

In this introduction chapter, background information about the identified problem is explained. Contribution of this research study and the study content is outlined.

1.1. Background Information

In recent years, negative impacts of growing construction industry have been increased. In parallel, the concern about the sustainability of buildings has also increased (Saraiva *et al.*, 2018). For example, protection of the resources and ecosystem is main focus of the environmental sustainability, while purpose of economical sustainability is to provide long term resource productivity and, low maintenance and operational cost. In addition, social sustainability covers social and cultural aspects that directly associated with human and culture (Kohler, 1999).

In Turkey, 33.74% of the total generated energy was obtained from fossil fuels that is the primary source of the CO_2 (Figure 1.1). Therefore, reducing energy consumption is important for reducing amount of the greenhouse gas emission (Development Directorate of Strategy, 2018).

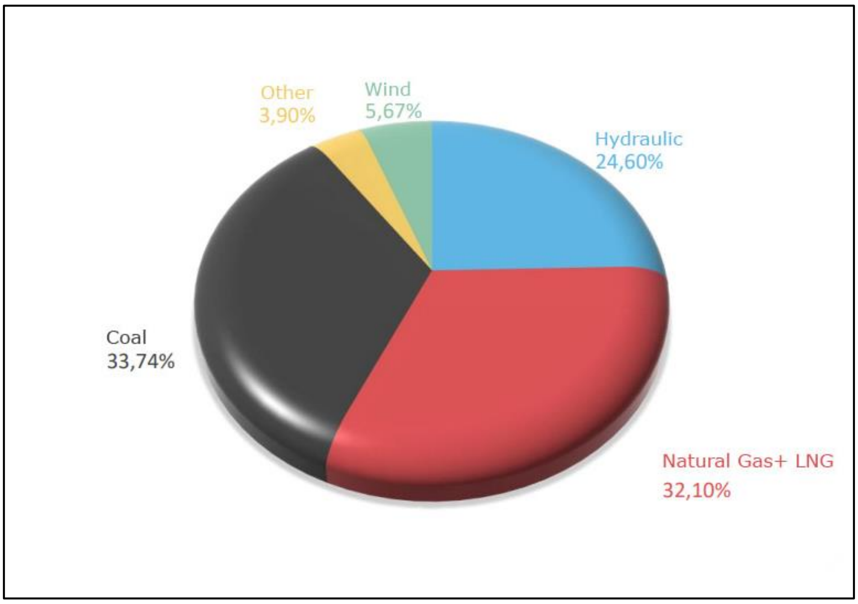


Figure 1.1. Electricity production rates by source at the end of 2016 (Development Directorate of Strategy, 2018)

According to TEDC report of 2017 (TETAŞ, 2017), government buildings' energy consumption constituted 3.9 % of the total energy consumption of Turkey, while total energy consumption was equal to 231,234 GWh. Among the government buildings, school buildings that are highly in number, have consumed a large amount of energy. Existing physical conditions of the buildings, low performance building materials, old technology mechanical and electrical systems and unconsciousness of the building users about energy efficiency are the main reasons of the high energy consumption in them. In addition, architectural design decisions, project site features, building orientation and differences in climatic regions also directly affect the building performance.

In addition to these issues, employment of standardized (prototype/type) school projects that is generally preferred for rapid school building production is inefficient in terms of sustainability. In this type project applications, coincidental decision about orientation, project site plan, material selection, *etc*. directly affect the building energy performance and sustainability of the buildings. Moreover, regulations about school buildings in Turkey do not address about these problematic issues.

Moreover, it should be considered that school buildings have a very high occupancy rate compared to other building types and students spend about 25% of their time in school building (Saraiva *et al*., 2018). Therefore, school building physical condition is also critical for students' health and productivity. Moreover, sustainable school itself is directly a learning source for students in early ages and it increases awareness about sustainability.

As a result, existing school building have great improvement potential in terms of sustainability and retrofits of existing school building is essential for increasing sustainability. Building retrofit has different direct and indirect benefits on building users and society, respectively. While building retrofits enable the decrease of energy load of the buildings, living conditions of the building users can also be improved at the same time.

In addition to all these topics, local climatic condition is one of the critical factors that directly affect the building performance and that should be considered for deciding energy retrofit types. Defining retrofit strategies in accordance with climate characteristics is a requirement to increase environmental, social, and economic sustainability of school buildings. It should be noted that energy retrofit measures do not have the same impact on sustainability in different climate regions

1.2. Aim and Objectives

The aim of the research is to evaluate sustainable impact of energy retrofit measures that proposed for type school buildings in different climate regions. To achieve this aim following objectives were fulfilled;

•To analyze existing school building problems in terms of sustainability in Turkey.

•To investigate retrofit measures for school buildings

•To evaluate the energy retrofit measures in terms of sustainability criteria: ecological, economic and social sustainability

•To evaluate the effect of the climate on performance of retrofit measures

•To investigate sustainability impact of retrofit measures in different climate regions.

1.3. Contribution

There are many researches in the literature that analyze school buildings in terms of energy efficiency and sustainability and there are various studies that investigate the energy efficiency of buildings in specific climates. In other words, these studies are generally based on a certain project and certain climate zone. However, there is no general framework that covers energy retrofit strategies for school buildings in different climate zones and their impact on sustainability. Therefore, this research presents the sustainability impacts of the energy retrofit measures in different climate regions, as a contribution to school building retrofit projects as a guide.

1.4. Disposition

This thesis includes five chapters. While the first chapter is introduction part, second is literature review chapter that gives information from literature on sustainability, school building sustainability, sustainability assessment methods and energy retrofit measures.

In third chapter, material and method of the study is explained and this part starts with the general information about sustainability assessment methods and selected assessment techniques. After that, selected materials of this study that are the selected type school project, proposed retrofit types and climates characteristics, are presented in material selection part. In data collection section, these materials are described in detail and proposed case studies and analysis methods to be used for evaluation of these in terms of sustainability are described in data analysis section. In addition, the parameters in the process of sustainability impact assessment and related hypothesis are outlined.

In fourth chapter, analysis that is defined in the third chapter is completed and the result of these analysis are presented with comparative graphs and tables. According to given data, the parameters of these analysis are discussed.

In the conclusion chapter, summary of the research study is explained. In addition, the results of the analysis are interpreted and concluded. Finally, limitation of the study and recommendations for future studies are stated.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature related to thesis topic is reviewed and information from literature are grouped under four main headings: Sustainability, Sustainability Assessment Methods, Energy Retrofit Measurements for School Buildings, and Effects of the Climate Characteristics on Sustainability.

In the ‘Sustainability’ part, sustainability, the subjects that are school buildings sustainability and sustainability of existing school buildings in Turkey, are explained. In the second part, sustainability assessment methods are presented and in the third part, information related to energy retrofit types are given. In the final part, the effect of climate factor on sustainability is explained based on the related research studies. At the end of this chapter, the literature on thesis subject is critically reviewed.

2.1. Sustainability

Sustainability is described as the ability to maintain, support and continue an action or activity for a long-term with sempiternity approach. It also aims to meet today’s needs with considering the needs of future generations and without compromising on the capability of meeting their requirements (Vatalis *et al.,* 2011). Sustainability concept includes the impact of the building about the environment and energy production and utilization. Moreover, it considers comfort of the occupants of the building and also has an economic viewpoint (Bruni *et al.,* 2013).

ISO 15392 standards define three primary aspects of sustainability (2008). These three domains in a common framework of sustainability that covers human comfort and health, resource consumption, cost; are ecological sustainability, economic sustainability and social sustainability (Kohler, 1999).

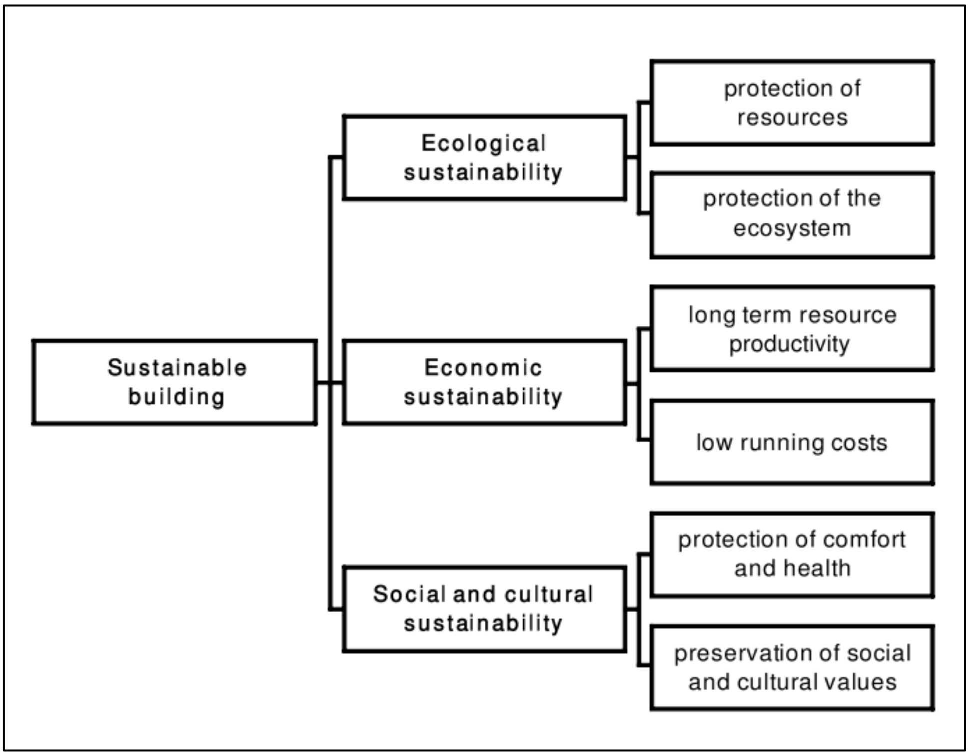


Figure 2.1. Three dimensions of sustainability and some related objectives for buildings

While ecological sustainability focusses on two main topics that are protection of resources and the protection of the ecosystem, economic sustainability aims to provide long term resource productivity and low running cost. Therefore, economically sustainable solutions proposed minimum maintenance and operational cost and, maximum durability and reusability (Figure 2.1). In this respect, initial cost is not the only parameter of the economic sustainability and, for providing economically sustainable building, life cycle cost should be also considered. In addition to economic and environmental sustainability, social sustainability involves social and cultural aspects that are directly related to human health and comfort, and cultural resources.

When considered from cultural sustainability point of view, conservation of the heritage of the city in terms of architectural, city planning, and landscape architecture came into prominence (Kohler, 1999).

Since the 1970s, the concerns of architecture have been gradually increasing in terms of local climate, human comfort and the environmental impact of buildings. Based on these concerns, bio-climatic architecture has come to the forefront. With this concept, architecture is responsible for providing the visual, cultural, emotional, ergonomic, acoustic and hydrothermal satisfaction of the users by providing the relationship between the local climate and indoor conditions. In recent years, the negative impacts on the environment have been increased by growing construction industry and public concern about the sustainability of buildings has increased (Saraiva *et al.,* 2018).

For the evaluation of the sustainability, there are various certification protocols that are suggested by independent and international associations and aimed to evaluate the building in terms of energy efficiency, health and comfort. Among some are Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM) and Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (Bruni *et al*., 2013).

2.1.1. Sustainability in School Building

School buildings are one of the most important types in built environment considering that students spend about 25% of their time in class. In addition, school buildings have a very high occupancy rate when compared to all other building types. Therefore, level of sustainability is very important for supporting students’ health and intellectual performance (Saraiva *et al.,* 2018).

Sustainability is a necessity for school buildings because of the contribution to environmental protection, improving quality of life, lowering the cost and increasing success of the students and teachers. The subject of environmental education at the United Nations Conference on Human Environment held in Stockholm in 1972 has gained an international dimension. In the declaration; the importance of the attitudes and behaviors of people towards their environment was highlighted, with the words that' Humanity must protect and improve the environment for the present and future generations.' In addition, the declaration of the conference organized with the cooperation of UNESCO and UNEP in 1977 is a turning point as it provides an understanding of the place of environmental education in human education (as cited in Kocabaş & Bademcioğlu, 2016).

Based on the interview with Ministry of National Education on November 1, 2018, school buildings have an important position when compared with other building types due to the fact that users that are young and children. Moreover, the fact that they are the buildings aiming at education and learning, increases the importance of these buildings. However, due to the increasing need for school buildings, lack of time and financial resources, type project applications have been widely preferred in production of school buildings.

Following the foundation of the Turkish Republic in 1923, a centralized and unified education system was proposed as a solution to a very fragmented and non-standard school landscape across the country that was inherited from the Ottoman Empire. The Ministry of Education was given the responsibility for planning, design, and construction of public-school buildings. In the early years of the republic, private or foundation initiatives for provision of schools were very limited due to lack of wealth across the country. Some minority and foreign private schools were among few examples of non-governmental education facilities (Pekeriçli, 2018).

Like other governmental policies, a centralized management approach was chosen for delivering the duties of Ministry of Education. While this approach ensured standardization and strict compliance with the policies and goals of the state, it has overwhelmingly increased the workload of the government units. Throughout the second half of 20th century the increasing number of populations led to the need for constructing many large high schools. Since the ministry could not give up its duties as the central decision maker and executer of the school projects, it had to streamline the process. For that reason, a prototype architectural design was prepared in 1955 to be used for all secondary and high school projects across the country. This approach was chosen to simplify the tendering process, contracts, commissioning and control of construction quality for a limited team of civil servants at the Ministry of Education, and their representatives at the local directorate offices. The same prototype architectural design (aka type 735) was used to build thousands of schools spread across the country between years 1960 and 2000. There are varying quality of workmanship and small changes occurring throughout years, but these are negligible. After using the same project for half a century, the government commissioned new architectural prototype designs for schools between years 1998 and 2000, and also around 2008 (Pekeriçli, 2018).

While the standardized building projects streamlined the duties of the centralized government bodies, the ignorance of the vast geography, cultural diversity, and climatic zones of Turkey led to many operational problems during their use (Pekeriçli, 2018).

In addition, according to interview with Ministry of Education, school buildings show similarities with other public buildings in terms of working hours. They are usually used between 8 AM and 6 PM. Also, evening classes are offered in some schools.

School buildings have great improvement potentials about energy efficiency. Alajami (2012) stated that electrical and mechanical system retrofits of educational building provide up to 52% energy saving opportunity in Kuwait. In addition, with using proper thermal insulation, HVAC devices and shading equipment, 35.3% energy consumption can be achieved (Sait, 2013). Not only the retrofit of the electrical and mechanical devices, but also the utilization of control technologies helps to increase energy performance and decrease energy consumption (Bernardo *et al.*, 2017).

Providing sustainability criteria and especially decreasing energy consumption is important issue for existing buildings (Dumciuviene *et al.*, 2018). However, sustainability of school buildings is differentiated from other building types in terms of building function, users and owner. Since, school buildings offer living spaces for learning activity to students/children (Bruni *et al*., 2013) and school buildings shaped by the principles of the sustainability should be used as learning resource for students.

Therefore, it is important and beneficial to give a priority to the design of school building in terms of providing public consciousness about sustainability. It will be possible to introduce sustainability awareness to the designer and engineers of the future at a young age with various ways such as creation of guidelines for sustainable school design and development of sample projects for school. Thus, this should be considered because of the significant contribution of the sustainability (Şahin & Dostoğlu, 2015).

In addition, learning environment quality is very important for increasing the productivity of students. Therefore, providing thermal comfort, increasing indoor air quality, proper lighting environment and proper quiet atmosphere is very crucial for both learning and teaching facility (Bernardo *et al*., 2017). It can be said that for school building, developing indoor environmental quality is a necessity that support students' health and intellectual development. In order to improve the indoor environment quality, it is necessary to provide indoor air quality, visual comfort, acoustic and ergonomic comfort (Saraiva *et al.*, 2018).

Moreover, according to REHVA (as cited in Bernardo *et al*., 2017) children consume huge part of time in school and they are susceptible to low school indoor air quality. It is important that children get high quality air for their healthy growth. (Bernardo *et al.*, 2017) In this respect, environmental parameter such as pollutant and CO_2 concentration, air humidity and air temperature should be controlled (Saraiva *et al*., 2018).

Educational buildings express the values of individuals who are part of the society in different ways. The conditions and needs of educational buildings built in urban or rural areas are different. In addition to that, the messages they give to society are also different. For this reason, it is very important to design and analyze the conditions and needs of the school in detail (Kocabaş & Bademcioğlu, 2016). According to Şahin and Dostoğlu natural lighting, heating and cooling methods, indoor air quality, wind energy, water saving, and material selection are also important criteria for sustainability (Şahin & Dostoğlu, 2015).

Lighting

Light is an environmental factor affecting body functions such as blood pressure, heart rate, brain activity and biorhythm. In addition, Barker states that good lighting, students and teachers make an important contribution to the preservation of eye health and visual acuity and, education under optimal conditions (Kocabaş & Bademcioğlu, 2016).

The use of daylight in schools is important for children who spend most of their time in school, in terms of mental activity and psychology. Furthermore, Edwards and Torcellini (2002) suggest that sunlight, the natural light source, is the main source of vitamin D. For this reason, students should benefit from these rays as possible (Edwards & Torcellini, 2002).

Considering the positive effect of natural light on learning, various studies have examined the ideal ratio between space and window dimensions. For example, according to Prakash and Fielding (2007), the class depth should be 1.5 times the window height (Figure 2) (Şahin & Dostoğlu, 2015).

In addition, different details should be considered to increase daylight intake. While the ceiling reflection can be used thanks to the light shelf adapted to the windows, controlled solar light can be provided to the interior with the movable façade panels.

Moreover, glare control, which is an important requirement for the training environment, can be provided with curtains or blinds (Şahin & Dostoğlu, 2015).

Although schools that have enough daylight affect students positively in many ways, Marenne and Semidor (as cited in Kocabaş & Bademcioğlu, 2016) state that a class cannot be illuminated with only natural light during the entire academic year. Therefore, it can be stated that lighting should be combined with artificial lighting when natural light is not effective during the day. In other words, it is more appropriate that natural and artificial light is not considered separately. Abdelatia *et al.*, (as cited in Kocabaş & Bademcioğlu, 2016) also indicate the necessity to know about the changes in daylight (movements related to the day and the season) to determine the need for artificial light (Kocabaş & Bademcioğlu, 2016).

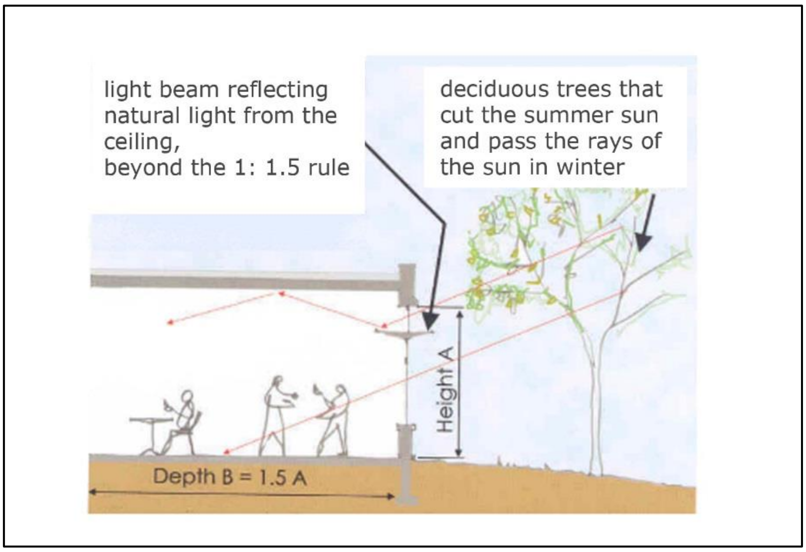


Figure 2.2. Proportions for class and ideal light intake (as cited in Şahin & Dostoğlu, 2015)

In the selection of lighting element, the impact on the energy consumption connection and health is evaluated. There are various lighting technology alternatives in terms of visual comfort conditions and lighting energy efficiency (Şener Yılmaz, 2016).While common lighting such as incandescent, fluorescent and halogen lamps have low efficiency, LED (light-emitting diode) solid-state lights that has long life-time and low maintenance can be more efficient lighting alternative (Koh *et al*., 2011).

Heating and Cooling Methods

Another factor that affects the student physically and psychologically is the temperature of the classroom environment. Extremely hot environments cause distraction and carelessness, while extreme cold environments cause attention and energy to warm up. Thermal comfort is considered as an important factor for the quality of the interior environment. According to ASHRAE 55 Standards, thermal comfort is the state of thought that is satisfied with the thermal environment. Thermal environmental properties are the determinants of thermal comfort. Although thermal environmental properties can be measured, thermal comfort is not a measurable value. For example, the temperature of the walls, floor and ceiling, glass and door surfaces constitute thermal environment that can be measured (Kocabaş & Bademcioğlu, 2016).

Environmental and individual factors are effective in determining thermal comfort. Environmental factors are defined as humidity, temperature and air movement, while individual factors are defined as clothing and activity levels. In this respect, according to Murphy and Thorne (as cited in Şahin & Dostoğlu, 2015), it is appropriate to have at least 18°C temperature in the school departments with a normal activity level, whereas the temperature is at least 15°C in places where students are more active (Şahin & Dostoğlu, 2015).

According to Ekici (as cited in Kocabaş & Bademcioğlu, 2016), based on an equation called mean thermal sensation, an indicator chart was created on how thermal values are perceived by the individual. If the individual does not complain about the thermal conditions of the environment in which he / she is located, this status is represented as

0, *i.e*., neutral. According to this chart translated from Turkish, it is accepted that an environment between ± 0.5 values is comfortable (Kocabaş & Bademcioğlu, 2016).

Table 2.1. *Thermal sensation indicator chart (Kocabaş &Bademcioğlu, 2016)*

PMV Value	Meaning	Comment
3	Too hot	Sweating and flushing begin
2	Hot	Heat discomfort and sweating begins
1	Slightly warm	Less disturbed by heat
0	Neutral	No complaints of heat or cold
-1	Slightly cool	Less disturbed by cold
-2	Cool	Heat disturbance and tremor begin
-3	Cold	Some organs come to the point of freezing

The issue that needs to be considered in terms of design is to reduce the overall energy demand to the lowest level by using passive systems. In passive systems, it is considered how to minimize the heating requirement of the building envelope, how best to use the context (adaptation, infrastructure, layout and micro-climate), selecting the least pollutant as fuel and minimizing the heat requirement (Şahin & Dostoğlu, 2015).

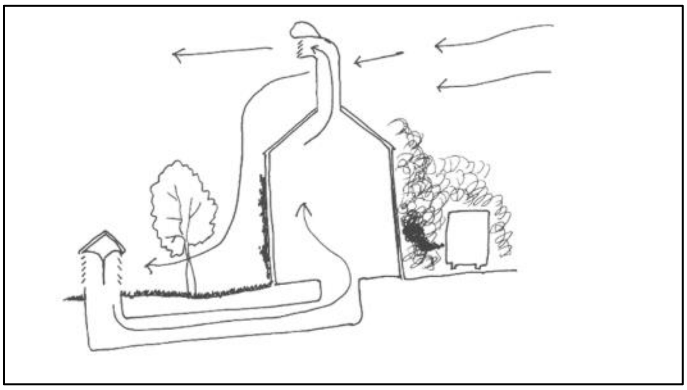


Figure 2.3. Graphical representation of the channel system providing preheating and cooling (as cited in Şahin & Dostoğlu, 2015)

In this respect, geothermal heating and cooling solutions that is using soil heat for preheating or cooling effect of the air passing through the channels created under the ground are recommended for winter and summer usage. Thanks to these alternative solutions, students are educated in a suitable environment as well as energy savings (Şahin & Dostoğlu, 2015).

Indoor Air Quality

According to Fanger, indoor air quality; it is considered as a measure of how good or bad the air in the indoor environment is (as cited in Kocabaş & Bademcioğlu, 2016) Following the oil crisis in the early 1970s, the increase in oil prices caused energy savings to gain importance. In order to save money, the buildings were covered with a shell with almost no permeability and the windows were kept closed (Kocabaş & Bademcioğlu, 2016).

Today, people often spend most of the day in closed spaces and crowded places. In addition, the use of natural products decreased in these areas. Wood, marble and natural fibers are replaced by petroleum products that have the ability to dissipate in indoor air such as fiberboard, synthetic fibers and plastics (Kocabaş & Bademcioğlu, 2016). In poorly ventilated environments, there is an increase in indoor pollutants (Şahin & Dostoğlu, 2015).

The low quality of the air in these environments also negatively affects the health of the people living in it. Besides, it can be stated that the use of natural building materials in order to increase indoor air quality is effective in solving environmental problems as well as on student and teacher health and efficiency (Kocabaş & Bademcioğlu, 2016).

There are many different factors in the buildings that will negatively affect the indoor air quality. Poor ventilation, high temperature and humidity are some of these factors. Due to insufficient ventilation, organic and inorganic contaminant concentrations in particulate and gas phase cannot be diluted, while high temperature and humidity can also lead to condensation of some indoor air pollutants (Kocabaş & Bademcioğlu, 2016). In this respect, volatile organic compounds, carbon dioxide, ozone and carbon monoxide can be kept at the desired level by means of ventilation in schools (Şahin & Dostoğlu, 2015).

These factors also affect human health negatively. Moreover, in the study of Yurtseven (as cited in Kocabaş & Bademcioğlu, 2016) states that indoor air quality has a significant impact not only on health but also on productivity. In addition, students and teachers exposed to indoor air pollutants decreases. Besides; Bulgurcu, İlten and Coşgun (as cited in Kocabaş & Bademcioğlu, 2016) emphasize that problems such as the lack of crowded classes, short breaks, unfavorable ceiling heights, and lack of mechanical ventilation cause problems in health and efficiency in schools (Kocabaş & Bademcioğlu, 2016).

Renewable Energy

Wind energy is one of the renewable energy sources that are important for sustainability and wind energy can be used independently or integrated into a building (Şahin & Dostoğlu, 2015). According to Yudelson (as cited in Kocabaş & Bademcioğlu, 2016) there are three major benefits of systems utilizing wind energy. First, these applications enable the building users to be aware of renewable energy sources. Secondly, it is highly demanded by architects and owners due to the remarkable appearance of wind turbines. The third is the use of wind turbines as a learning tool in order to create sustainability awareness in schools and environmental education centers (Kocabaş & Bademcioğlu, 2016).

In addition, solar energy is also another renewable energy source that can be used for school building energy consumptions. Photovoltaic (PV) panels are devices that generate electrical energy from sunlight (Hafız *et al.,* 2018). They can be easily applied on rooftops and sun facing surfaces.

Water Saving

Water conservation has an important place in the school buildings within the framework of sustainability. Different applications such as the accumulation of rain water, the use of a pool to provide air conditioning, and the use of gray water in the toilet can be employed in school buildings. In addition, dry urinals used to reduce the flow of water spent in toilet bowls may also be an alternative. It is very important for the children to be seen and included in the activities related to water conservation in order to gain awareness of environmental protection (Kocabaş & Bademcioğlu, 2016).

2.1.2. Sustainability of Existing School Building in Turkey

According to the Ministry of National Education Statistics (2018), the total number of educational institutions in Turkey is 65,568. 53,870 of them are public institutions and 11,694 of them are private institutions. In addition, according to the interview with Ministry of Education, there is no information about existing school projects conditions, number of type plan school projects and their locations. However, it is known that huge part of the school buildings is based on type plan project and they were constructed with some major or minor changes such as thermal insulation, window glazing, building envelope, building material *etc.* in different time.

It is seen that type school projects are implemented in school buildings as a method of producing fast and suitable school buildings in Turkey. However, these applications are appropriate at first glance in terms of cost. The significant shortcoming of the applications causes the school to be deprived of their architectural features. Land use and site plan settlements are the common negative aspect of the type projects (Köse & Barkul, 2012).

In addition, important changes have been made in type plans due to difficulties in finding urban land and rapid population growth and during adaptation of the project to the environmental conditions, additional cost occurs (Köse & Barkul, 2012).

Since public institutions and planning organizations responsible for planning and implementation do not have any model or decision for the spatial distribution of educational buildings, the choice of place for educational buildings is incidental (Köse & Barkul, 2012).

Rule and regulations are important guide for both existing and new projects in terms of achieving sustainable project. However, like in other developing countries, the importance of the sustainable school building has only recently been accepted and sustainability topic has not been adequately included in laws and regulations (Arslan, 2017).

In Turkey's building law and regulations; building location, form, sun and natural ventilation control systems are not specified. However, these factors directly affect the building energy performance according to climate region. In addition, material selection and thermal permeability coefficient that is also not included in regulations, is very important and critical for building energy performance (Tuna, 2009).

In recent years, the importance given to the concept of sustainability in design and construction process has increased in Turkey. For healthy generations in Turkey, where high ratio of young population, more healthy building design should be carried out in schools (Köse & Barkul, 2012). Although Turkey does not have a sustainability evaluation system such as LEED (Leadership in Energy and Environmental Design) and BREAM (Building Research Establishment's Environmental Report), these institutions are applied to obtain a certificate for the projects realized in Turkey. According to research of Şahin and Dostoğlu (2015), 24 projects which have different functions have been certified by BREAM. Piri Reis University, Automotive Industry Exporters Union Technical and Industrial Vocational High School and Erkut Soyak High School are the educational buildings with BREAM certificate from Turkey. In addition, some of the buildings belonging to TED Rönesans Collage, Acıbadem University Faculty of Medicine and Özyeğin University are certified by LEED. Therefore, it is demonstrated that the awareness about importance of sustainability for educational buildings is developing in Turkey (Şahin & Dostoğlu, 2015).

2.2. Sustainability Assessment Methods

Determining building sustainability level is not simple issue that can be evaluated easily. Therefore, the performance of the buildings in terms of environmental, social, socio-cultural and economic criteria indicates the level of sustainability. According to Hawkes *et al.* (as cited in Waer & Sibley, 2005), at first, ‘selective environmental design’ principles that is related to climate, location, user comfort, material preferences, building components and energy sources is described for assisting architects and planners. Furthermore, the concept of ‘green’ was associated with building that utilize renewable energy sources such as solar energy and rainwater and use environment-friendly materials. The ‘green’ buildings, which have additional features compared to standard buildings, have a high market value and at the same time they have a high cost. Considering the operating costs and investment costs, structures made based on sustainability principles were found to be more reasonable than green structures. Therefore, unlike ‘green’ assessment models, which focus on the performance of buildings at the regional and local scale, sustainability assessment methods that address the national and international scale and include a wider concept have emerged. It can be said that sustainable development concept is an environmentally friendly want to meet people’s needs, while considering the social and economic aspects of these needs. Sustainable developments propose a continuous idea development cycle that targets the optimal result by providing balance between systems which are economy, environment and society (Figure 2.4.) (Waer & Sibley, 2005).

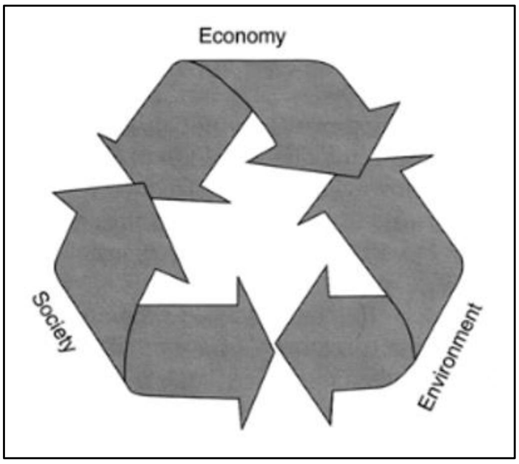


Figure 2.4. Idea development cycle for sustainable development (as cited in Waer & Sibley, 2005)

Benefits of the sustainable developments can be classified into three main benefits: economic, environmental and social benefits. For the sustainability assessment, the buildings can be examined in terms of these three categories (Jafari & Valentin, 2018). However, it should be also considered that sustainability indicators that measure the performance of the systems in the decision-making mechanism gain importance. Therefore, effective indicators in terms of economic, environmental and social issues should be based on accessible data and easy to understand while being relevant and reliable (Figure 2.5.) (Waer & Sibley, 2005).

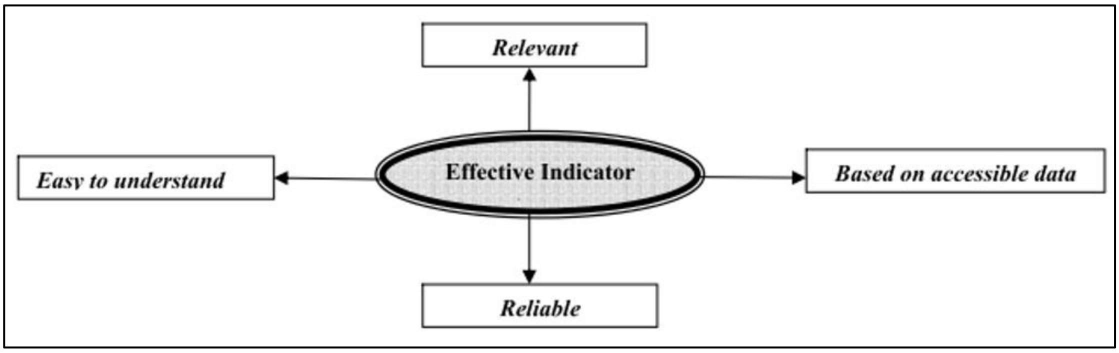


Figure 2.5. Effective sustainability indicators' characteristics (as cited in Waer & Sibley, 2005)

In the literature, there are many researches about the sustainability assessment of the building retrofit. Especially, economic benefits and environmental benefits of the retrofit projects were investigated many times. There are many studies in the literature about life-cycle cost (LCC) and life-cycle cost analysis (LCCA), payback period analysis, amount of greenhouse gases emissions, *etc*. However, in terms of social benefits, only a few studies are well improved and address this issue systematically (Jafari & Valentin, 2018).

2.2.1. Economic Sustainability Assessment

Sustainability in buildings have great potential in terms of economic benefits and, also environmental and social benefits. However, there is a misunderstanding that sustainable designs are expensive, and stakeholders such as owners, the public and operators have a lack of information on this issue. It is thought that sustainable solutions in terms of maintenance and procurement causes raising capital cost and decreasing market attractiveness by adapting innovation. Therefore, rather than in terms of sustainability, the stakeholders are primarily concerned with economic benefits and economic sustainability of the buildings (Vatalis *et al.,* 2011).

Economic sustainability can be measure in different ways and in different detail levels. It should be considered that project location, taxes, fees, permits, local and national conditions are project's features differ from project to project and in accordance with these features, the economy of each project is unique. Therefore, it is very hard to generalize sustainable solutions. In addition, it is difficult to determine potential benefits in terms of economy before the end of the projects. Since, building retrofits have positive impact on returns of investment in operation and maintenance phases.

In this respect, there are some assessment technics used to economically evaluate the buildings and investments (Vatalis *et al.*, 2011).

Payback period (PAY) is one of the economic measures used for the analysis of the building investment. It can be defined as the amount of time that is required for the recovery of the extra investment. Therefore, it can also be formulated as the ratio of the additional cost (PC) to the amount of annual reduced operating cost (OC) (Equation 1) (Mahlia *et al.*, 2011).

$$\Delta PC + \sum_{1}^{PAY} \Delta OC_t = 0 \tag{1}$$

In addition, if the annual reduced operation cost is constant value, the formula of the payback period can be simplified as Equation 2:

$$PAY = -\frac{\Delta PC}{\Delta OC} \tag{2}$$

The fact that PAY is more than the product’s lifetime is denoted that the additional cost is not recovered in decreased operating saving (Mahlia *et al.*, 2011).

According to Russell (2009), payback analysis is not a measurement related to profitability and it does not associate with interest rate or cost of money. Payback analysis is a risk assessment tool. Therefore, by making inferences from the payback analysis, it can be said that the investments with a short payback period are better than those with a long payback period (Russell, 2009).

Life-cycle cost (LCC) that is defined as total cost of the building in given period, can be a guide for the economic sustainability and useful in decision making process for construction (Jafari & Valentin, 2018). LLC technique comes into prominence with raising awareness on importance operational and maintenance cost of the projects and ‘value for money’ trend (Gundes, 2016).

Life-cycle costing is an important method for analysis of the sum of ownership cost from cradle to grave (Gundes, 2016). The differences in the total cost before and after retrofit are indicators of economic sustainability (Jafari & Valentin, 2018).

However, building LCC breakdown structure is very complicated and long-term uncertainties of the project in the future should be also well defined. LLCA constitutes of main cost components of the building in the process from construction to destruction. There cost components are: initial investment cost, operation and maintenance cost, repairs and replacement costs, energy cost, renovation cost, administration cost, taxation cost and finally disposal cost. In addition, inflation rate that effects the interest rate also should be considered for analysis of LCC (Jafari & Valentin, 2018).

Briefly, LLC includes various cost elements such as ‘project, utility and maintenance’ in different phases of the project’s life cycle. Project costs divided into ‘hard’ and ‘soft’ costs. While, hard costs are associated with construction costs, soft ones are the costs arising from design and permit prices. On the other hand, the cost of utility is related with the operational costs that is caused by the utilization of water, energy and sewerage. In addition, maintenance cost is changed with the selected maintenance strategies such as the routine preventive maintenance, reactive or planned maintenance. In planned maintenance strategy, it is assumed that the sub-systems will be renewed every five years and the cost of these renewals is involved in LCC. Moreover, while preventive maintenance is a strategy for minimize the maintenance cost, reactive maintenance is attempted after any problems happen (Gundes, 2016).

Briefly, there are also variable economic analysis methods for the building retrofitting investment assessment such as net present value (NPV), overall rate of return (ORR), internal rate of return (IRR), benefit-cost ratio (BCR), discounted payback period (DPP). According to the information to be obtained at the end of the analysis, one of these methods can also be preferred (Wang *et al*., 2014).

2.2.2. Environmental Sustainability Assessment

Providing energy efficiency in buildings has many benefits in terms of environmental such as CO_2 emissions, reduction of damage to nature and decreasing pollution loads. 39% of CO_2 emission is caused by building sector in United States. Heating, cooling, lighting equipment and other electrical equipment consume fossil fuels that cause CO_2 emissions due to combustion. Therefore, increasing energy efficiency of the building is important to decrease the threat of climate change by reducing CO_2 emission. Energy efficiency of the building provides to decrease the impact of the building to the environment during life-cycle. In addition, fossil fuel that is non-renewable energy resources is consistently generated via natural processes that take millions of years. Thus, conservation of fossil fuels such as coal, natural gas and oil and using renewable energy resources is also needed for conservation existing reserves are being depleted (Jafari & Valentin, 2018).

For assessing the environmental sustainability, green building rating systems are widely preferred method. In addition, there are many tools available for this purpose such as LEED, Green Globes, LBC, BREAM, CASBE, *etc*. While LEED, BREAM and LBC are international rating systems, CASBEE and Green Globes are used in Japan and; The United States and Canada respectively (Kamali *et al.*,2018).

In these rating systems, there are many categories such as sustainable site, energy efficiency, water efficiency, material and resources, indoor environmental quality, waste and pollution. In addition, each rating systems concentrate on these categories in different weights. For example, in the research of Magrini and Franco about environmental sustainability assessment of the historical buildings in Italy, the comparison of some rating systems in different categories is shown in the Figure 2.6. (Magrini & Franco, 2016).

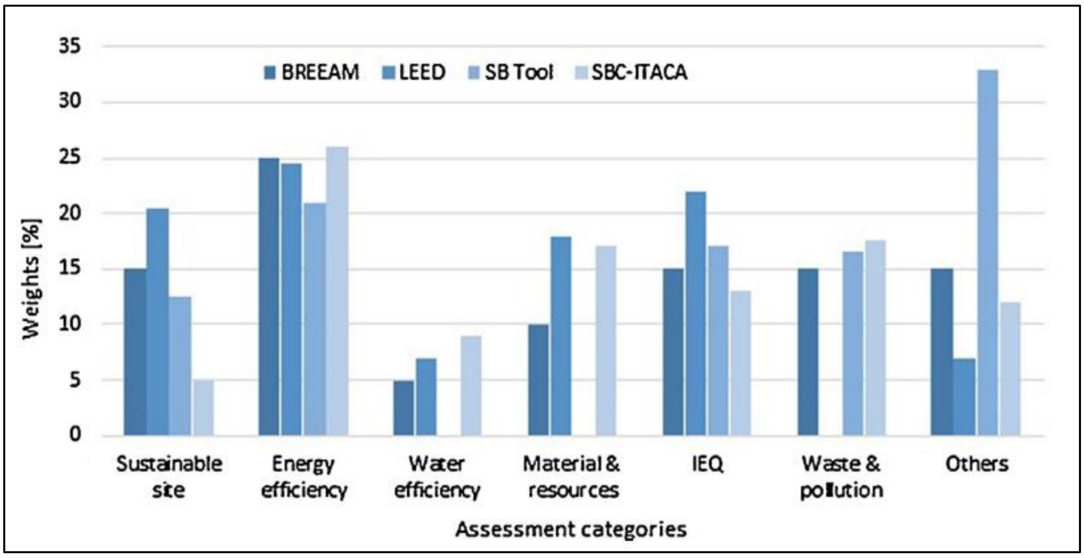


Figure 2.6. Sustainability assessment categories weight comparison (Magrini & Franco, 2016)

In order to evaluate environmental sustainability performance of the building, these rating systems defines a variable range of performance criteria and graded each project based on these performance criteria. Thanks to these systems, both current performance of the building and the expected performance can be analyzed, and it also enables to compare different building projects. Although these rating systems have many advantages, there are also some deficiencies of the rating systems such as complexity and variety of criteria, bureaucratic process of evaluation and cost factors related to certification (Kamali *et al.*,2018).

Another important method for assessing the environmental sustainability is Life-Cycle Analysis (LCA) and LCA-based tools. ATHENA (Canada, US), Eco-Quantum (Netherlands), BEES (US), EcoEffect (Sweden) and ENVEST (UK) are examples of LSA tools (Kamali *et al.*, 2018). LCA is also a method for evaluation of environmental performance by calculating of consumption of natural sources and amount of emission in production process (Asdrubali *et al.*, 2019). This method has a bottom-up approach and it means examining the effect of the whole building on the environment starting from the environmental impact of materials and building components (Kamali *et al.*,2018).

LCA has become popular with utilizing a functional tool to evaluating sustainability of the process or product from cradle to grave. Over years, it has been used for assessing cost and environmental impact of building components with the purpose of decision making and decision support (Gencturk *et al.*, 2016).

However, it is a very difficult and detailed process to handle sustainability in all dimensions including social dimension and integrate it into LCA (Gundes, 2016). LCA method is not only related to energy use impact such as climate change and fossil fuel depletion; but also associate with the factors such as land use, ozone depletion, eutrophication, acidification of water and land, human toxicity and water depletion. Therefore, LCA is very proper analysis method that can be used in retrofit early evaluation for the decreasing global environmental impact in whole building life (Asdrubali *et al.*, 2019).

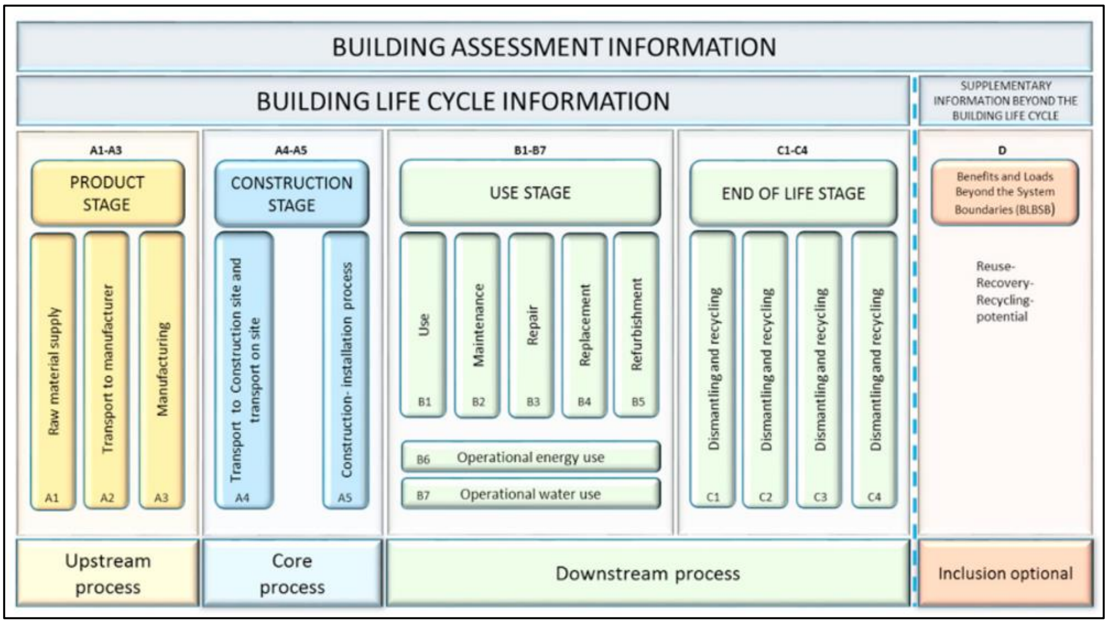


Figure 2.7. Example of the LCA stages

LCA is a complex analysis method that includes many uncertainties and a long time. In this process, there can be a lot of changes in many aspects, from the function of the building to the technology and the performance of the materials. For example, eco-profile of the building materials can be changed in time or retrofit applications enable to decrease the energy consumption caused by air conditioning, lighting, domestic hot water and equipment. However, LCA provide to analysis resulting load changes and environmental process control. In LCA, the materials are considered from the process of the extraction to the installation in detail. It provides a subjective assessment of the quality of the data used in the LCA analysis with the indicators listed in Figure 2.7. (Asdrubali *et al*., 2019).

2.2.3. Social Sustainability Assessment

Sustainable buildings have not only environmental and economic impact or benefits, but also a great social impact in terms of health, efficiency, user satisfaction and comfort. However, Labuschange and Brent (Zuo *et al.,* 2012) has been defined the social sustainability as 'weakest pillar of sustainable development' because of the lack of supportive elements in terms of analytical and theoretical. There are deficiencies in defining the guidelines of social sustainability measures (Zuo *et al.,* 2012).

Social Impact Assessment (SIA) is a methodology developed to evaluate the social impacts of intervention projects. The International Association for Impact Assessment clarified the SIA methodology in its 2015 guidance document. According to The International Principle for Social Impact Assessment, SIA is described as "the process of analyzing, monitoring and managing the intended and unintended social consequences, both positive and negative, of planned interventions (policies, programs, plans, projects) and any social change processes invoked by those interventions". In addition, social impacts cover all the subjects related with a project (intervention) that directly or indirectly interest people (Vanclay *et al.,* 2015).

Measuring and evaluating these social impacts is also important about assessing the level of sustainability of the building. To evaluate the social impact of the projects, the social benefits can be categorized into three levels: society levels, community levels and building levels. For example, energy efficient buildings contribute to the improvement of health by reducing the CO_2 emissions; it also creates a new job position for society (society level). In addition, energy efficient buildings ensure public awareness about sustainability and encourage public about energy retrofit application (community level). Moreover, energy retrofitting practice increasing building occupants' health and comfort (building level). According to Jafari and Valentin (2018) social effects of energy retrofitting can be categorized into four main topics (building level): health, comfort and satisfaction, productivity and security (Jafari & Valentin, 2018).

For example, while improving indoor air quality affects the health of the users positively, appropriate indoor temperature is important for the comfort and satisfaction of the users. In addition, appropriate temperature, light and air quality have great impact on productivity of the users. In this regard, Jafari and Valentine (2018) pointed out the importance of the use of renewable energy sources about ensuring the safety of power and onsite power systems are exemplified related to this subject by them. Furthermore, the actions related to sustainability is a source of pride and satisfaction for the users by considering the positive contribution to the future (Jafari & Valentin, 2018)

Consequently, there are many criteria that should be consider while evaluating sustainability of the buildings in terms of economic, environmental and social. According to Kamali *et al.* primary potential sustainability criteria that is proposed in his/her research, is shown in the Table 2.2. in terms of environmental, economic and social (Kamali *et al.*, 2018).

Table 2.2. *Sustainability performance criteria (Kamali et al., 2018)*

Environmental SPCs	Economic SPCs	Social SPCs
Site selection (SS)	Design and construction time (DCT)	Health, comfort, and well-being of occupants (HO)
Alternative transportation (AT)	Design and construction costs (DCC)	Influence on the local economy (ILE)
Site disruption and appropriate strategies (SD)	Operational costs (OC)	Functionality and usability of the physical space (FU)
Renewable energy use (RE)	Maintenance costs (MC)	Aesthetic options and beauty of building (AB)
Energy performance and efficiency strategies (EP)	End of life costs (EC)	Workforce health and safety (WHS)
Embodied energy (EE)	Durability of building (DB)	Community disturbance (CD)
Water and wastewater efficiency strategies (WE)	Investment and related risks (IR)	Influence on local social development (ISD)
Regional (local) materials (RM)	Flexibility of building (FB)	Cultural and heritage conservation (CHC)
Renewable and environmentally preferable products (REP)	Integrated management (IM)	Affordability (A)
Waste management (WM)		Safety and security of building (SSB)
Greenhouse gas emissions (GE)		User acceptance and satisfaction (UAS)
Material consumption in construction (MC)		Neighborhood accessibility and amenities (NAA)

2.3. Energy Retrofit Measures for School Buildings

Sustainability of school buildings can be measured by the effect of the ecosystem and near environment. Retrofit of school buildings that constitute an important part of the existing building stock is very critical. Sustainable school buildings have low construction and operational costs and they provide social and ecological efficiency (Arslan, 2017).

Building retrofit has various direct benefits for building users and indirect benefits for society. While it helps to reduce building heating and cooling loads, it also increases indoor air quality and improves living conditions of the occupants. In addition, social benefits of the building retrofits are 'non-tradeable goods' of the building retrofit (Friedman *et al.*, 2014).

With state of art technologies, upgrading of building components with high performance ones and utilizing building control strategies provides optimized energy performance. Therefore, retrofit strategies designed with a holistic approach have a significant impact on the efficiency of the whole system (Sweetser, 2012).

In addition, not only the energy performance of the building components, but also the convenience of these with climatic conditions of the building location should be focused while deciding proper retrofit strategy (Liu & Ren, 2018). Moreover, demand and supply measures should be taken into consideration at the same time. Thus, achieving optimal energy retrofit solutions in terms of sustainability, is a major concern and it is possible with appropriate retrofit measure choices (Donnarumma & Fiore, 2017).

According to studies in the literature about school building retrofits are examined in different categories such as building envelope, mechanical system, electrical system, architectural solutions, renewable energy sources.

2.3.1. Building Envelope

Building envelope is the main factor that prevent energy flowing into and out of the building. With decreasing heating and cooling loads cause, energy use of the building can be reduced (Fan & Xia, 2017). Building envelopes can be categorized into three main topics: walls and roofs insulation and, window and door replacement (Friedman *et al.*, 2014).

For increasing air tightness and decreasing thermal conductivity of walls, thermal insulation materials is required with various thickness and types. In the application of these materials, there are some extra labor and materials. For example, for external walls insulation application, stucco rendering, painting ad scaffolding works are involved and for internal insulation application, gypsum boards on metal frame, new window frames and painting are also included (Friedman *et al.*, 2014).

Thermal insulation thickness is also important for providing economical sustainability. According thickness of the insulation layer, thermal efficiency and also cost of the insulation material change. Therefore, proper thickness insulation material is should be considered for maximizing energy and minimizing payback period (Friedman *et al.*, 2014).

External wall thermal insulation helps to eliminate thermal bridges, while internal wall insulation has difficulties about reduction of thermal bridges. In addition, internal wall insulation can affect the internal net floor area. However, external wall insulation has no impact about internal net floor area. Moreover, internal acoustic can be improved by using internal wall insulation (Sauchelli *et al*., 2014).

For roof part of the building, using thermal insulation and using high albedo paint is main preferences of the energy retrofit. Building roof retrofit improves roof thermal performance without reduction of internal net area. In addition, it also provides reduction and resolution of most of thermal bridges (Sauchelli *et al*., 2014).

White color roofs are useful especially in warm climates, helping to reduce cooling energy loads. In addition, this cost-effective method that needs to be renewed in 5 years makes contribution to urban waring and global climate change. For insulation of the roof insulation panels like extrude polystyrene panels can be preferred with water proofing layers and gravel ballast in flat roofs. Green roofs also contribute to urban warming, but it should be considered that maintenance of the green roofs cannot be cost effective in every climate region (Friedman *et al.,* 2014).

For the window parts of the building, decreasing thermal conductivity, providing air tightness and sunlight control are the main parameters. While double glaze windows help to reduce heat loads in winter, it also reduces heat gain in summer (Friedman *et al.*, 2014).

Likewise, double ventilated windows also decrease energy demand by preventing heat losses because of ventilation and preheating ventilation air. According to case study on school building, up to 1000 kWh/year of additional energy gain from preheating ventilation air can be achieved with utilizing double ventilated windows (Carlos & Corvacho, 2010).

In addition, film coated window provide sunlight control in warm and hot climate regions. Moreover, utilizing overhang, vertical fins and operable blinds are also reduced heat gain in warm and hot climate (Friedman *et al.,* 2014).

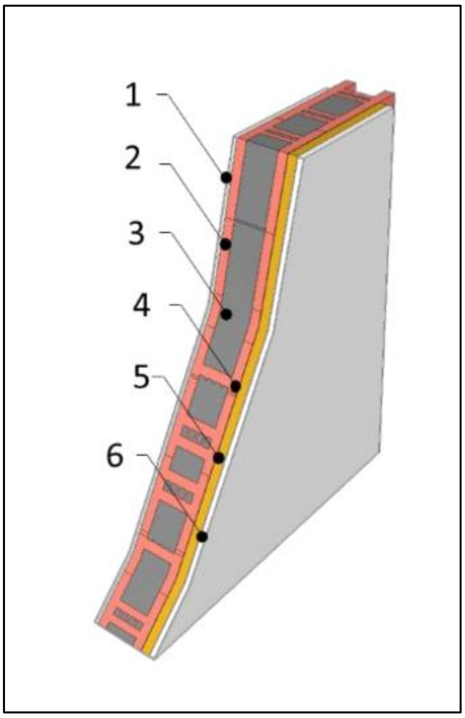


Figure 2.8. Composition of wall with ETICS: (1) lime plaster (15 mm); (2) hollow brick (220 mm); (3) concrete (200 mm); (4) adhesive mortar (1.5 mm); (5) mineral wool (35 mm); (6) lime plaster (25 mm) (Urban *et al*., 2018)

With development of technology, External Thermal Insulation Composite Systems (ETICS) Technology was developed. ETICS is a multilayer complex system that has various advantageous features. Multilayer structure satisfies the needs of specific performance standards and application methods (Sulakatko & Vogdt, 2018). ETICS contains thermal insulation layer, thin solid layer of plaster like material layer and finishing layers from inside to the outside (Figure 2.8.). While ETICS increase the thermal performance of the building, it also provides moisture infiltration. The main difficulty of the ETICS to develops the thermal insulation properties of the building while developing other necessary building physic parameters and appearance of architectural aesthetic (Urban *et al.*, 2018).

According to study of Sauchhelli *et al*. (2014), effect of the building envelope retrofit on heating energy demand clearly shown in Figure 2.9. Adapting new windows reduced energy requirement for heating by 39.6% compared to the baseline model. In addition, reduction of the heating energy demand increases to 61.3% compared to baseline model by adding thermal insulation with new window. In addition, when these retrofits are supported with heat recovery systems, heating energy demand is decreased by 70.8% according to baseline model heating energy demand (Sauchelli *et al*., 2014).

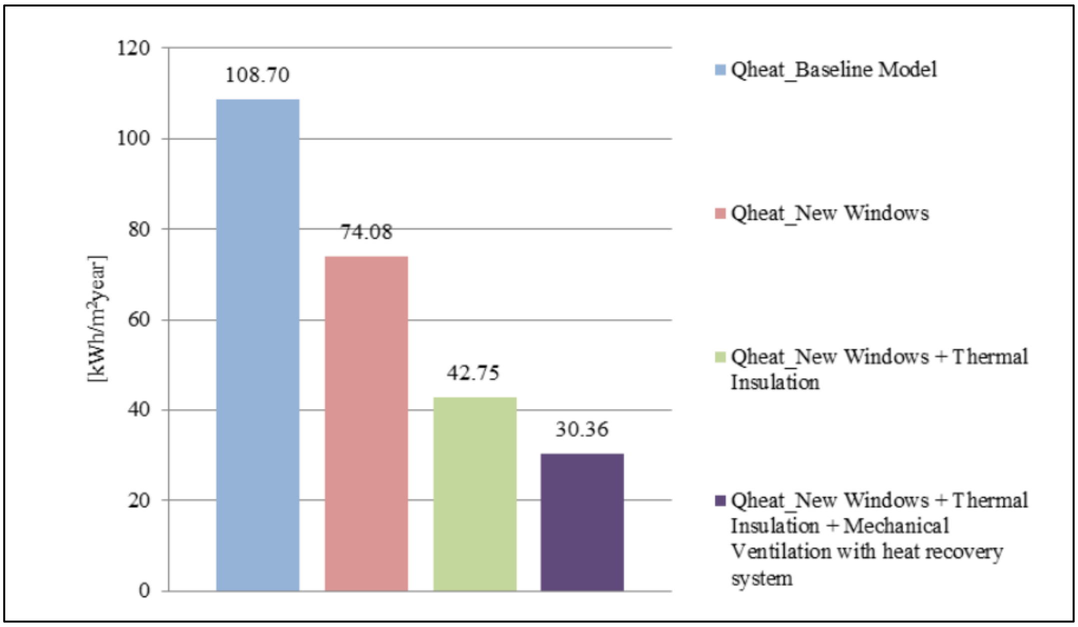


Figure 2.9. Heating energy demands of different scenarios compared to baseline model (Sauchelli *et al.*, 2014)

2.3.2. Mechanical System

According to Sauchelli *et al.* (2014), integration of passive solution and active strategies such as upgrading mechanical systems and controls decrease the building energy demand up to 70% (Sauchelli *et al*., 2014).

Heating and ventilation are the most energy consuming system in the building. Outdated equipment and inappropriate operational systems consume more energy than necessary (Wang *et al.*, 2017). Thus, mechanical system retrofit can be categorized into two parts: ventilation system and heating system.

Ventilation

Energy recovery is the method of the reducing energy consumption of the system by transferring the energy between sub-systems Figure (2.10.). With this method one output energy of one sub-system can be used as input energy of another subsystem. Therefore, total energy consumption of the system is reduced due to waste energy utilization (Kassai, 2017).

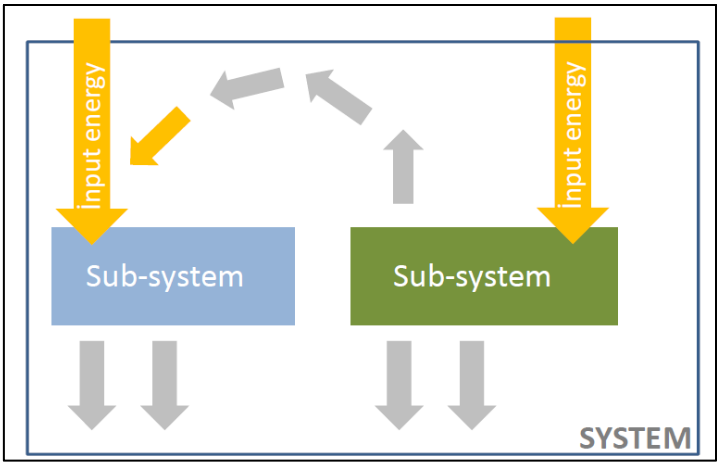


Figure 2.10. Energy recovery principle

According to Perez-Lombard (as cited in Ribe *et al.*,2019), total energy consumed and wasted by HVAC systems constitutes 50% of the total energy consumption of the building. In air conditioning process, thermally conditioned air removed from building through exhaust ducts and windows without recovery. Since, important part of the energy exhausted from the building due to ventilation (Ribe *et al.,* 2019).

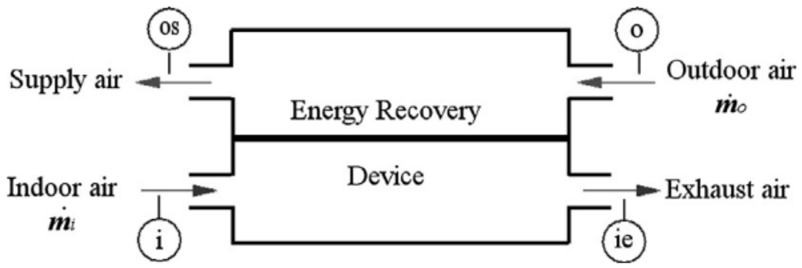


Fig. 1. Schematic of an energy recovery device.

Figure 2.11. Schematic of an energy recovery device (Ribe *et al.,* 2019)

In air conditioning systems, to decrease total energy consumption air to air heat exchanger can be used. Thereby, energy inside exhaust air is transferred to supply air by heat exchanger (Figure 2.11.). There are two types of heat exchanger: heat recovery ventilation (HRVs) and energy (enthalpic) recovery ventilation (ERVs) (Al-Zubaydi & Hong, 2018). While in HVRs systems, only sensible heat is recovered; in ERV systems, sensible heat and latent heat recovery is provided. In ERVs, sensible heat inside preconditioned indoor air is conveyed to fresh outdoor air. In addition, ERVs not only used for transfer of the sensible heat, but also latent heat that comes from humidity in exhaust air (Ribe *et al.,* 2019).

Thus, in air conditioning systems, requirement of the heat recovery units is not only for the heat energy recovery, but also condensation problems of indoor air can be eliminated by using energy recovery units. According to season (warmer and cooler) energy recovery units can be used to dehumidify or to humidify indoor air (Kassai, 2017). In addition, climatic condition is also important parameter for the efficiency of the ERVs and HVRs (Ribe *et al*., 2019).

Heating

According to research of the Minister of Natural Resources Canada (as cited in Kose & Petlenkov, 2016), Earth absorbed 46% of the Sun's energy. Due to high storage capacity and slow heat exchange characteristic of the ground, Ground Source Heat Pump (GSHP) systems use the renewable source of energy in earth and groundwater (Kose & Petlenkov, 2016). Ground heat exchangers (GHE) part of the GSHP systems provides using earth temperature as 'heat source or heat sink' (Kim *et al*., 2012).

While in cooling seasons, this energy can be used for providing low temperature heat; in heating seasons, for opposite purpose. While, GSHP systems have economic advantages because of reduced heating and cooling demand, it also has environmental benefits due to reduced CO_2 emission (Kose & Petlenkov, 2016). In addition, compared with air source heat pump (ASHP), GSHP has high energy efficiency. In heating season, ASHP systems utilize the higher temperature atmosphere; while GSHP systems use lower temperature of ground. Hence, energy efficiency of the GHSP is higher than ASHP systems (Kim *et al*., 2012).

Annual temperature balance of the ground should be considered in GSHP systems. If there is a short-term change in ground temperature, GSHP systems cannot achieve successful results (Androulakis *et al.*,2018).

GSHP system can be integrated with solar thermal energy and these combined systems are called as solar-assisted ground source heat pump systems (SAGSHPS). Heat energy comes from solar thermal equipment's is charged to boreholes of the GSHP systems and it enables to increase soil temperature. Therefore, GSHP used as heat sinks that can be reduced heating energy demand in long term. According to study of Androulakis *et al.* (2018), utilizing SAGSHPS systems in school building decrease the primary energy consumptions. However, area of the solar collectors should be considered as it increases the installation cost significantly (Androulakis *et al.,* 2018). Therefore, utilizing GSHP systems has recently increased (Kose & Petlenkov, 2016).

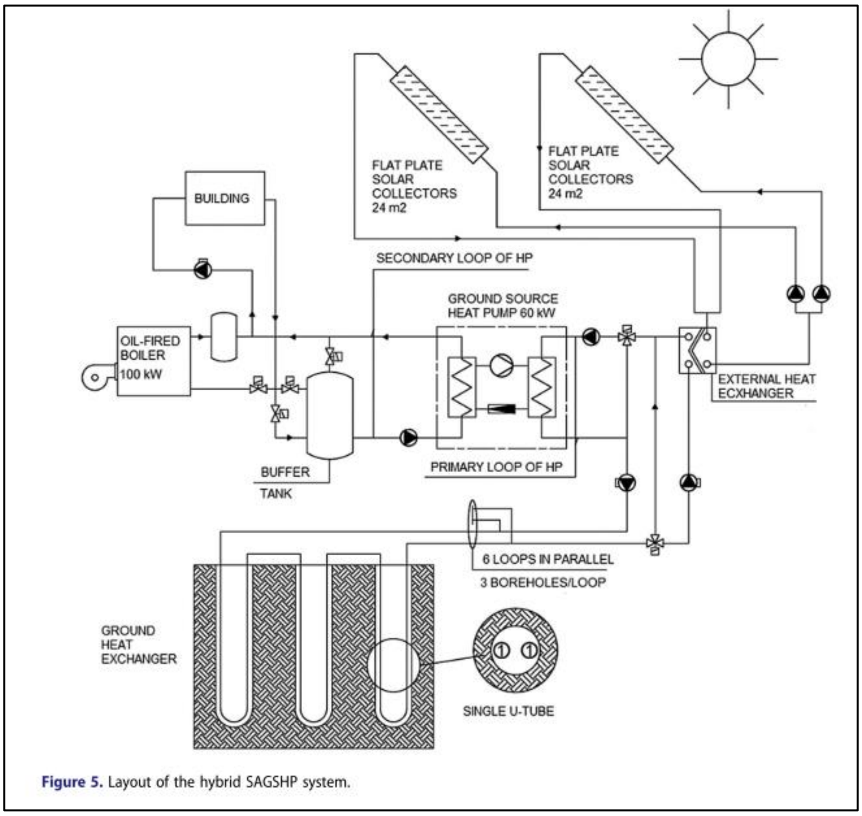


Figure 2.12. Layout of the hybrid SAGSHP system (Androulakis *et al*.,2018)

Cooling

Because of the high energy consumption of the traditional air conditioning system, environmental-friendly and economically sustainable air conditioning methods become more important. Evaporative air conditioning system is an example of them and according to contact type it is separated into two categories: direct evaporative coolers (DEC) and indirect evaporative coolers (IEC) (Sohani & Sayyaadi, 2017).

DEC contains four main part that are wetted pads, a water sump, an electric motor with fan and water pump system (Figure 2.13.). Supply air passing through the wetted pads, some part of the water is evaporated and amount of sensible heat of the supply air decreased. Therefore, while dry bulb temperature of the supply air is reduced and humidity of it is increased (Jaber & Ajib, 2011).

In IEC systems, heat exchanger is adapted into the system instead of wetted pads and there is no direct contact between cooled humid and supply air. While this process improves the comfort level of air, humidity ratio remains constant (Jaber & Ajib, 2011).

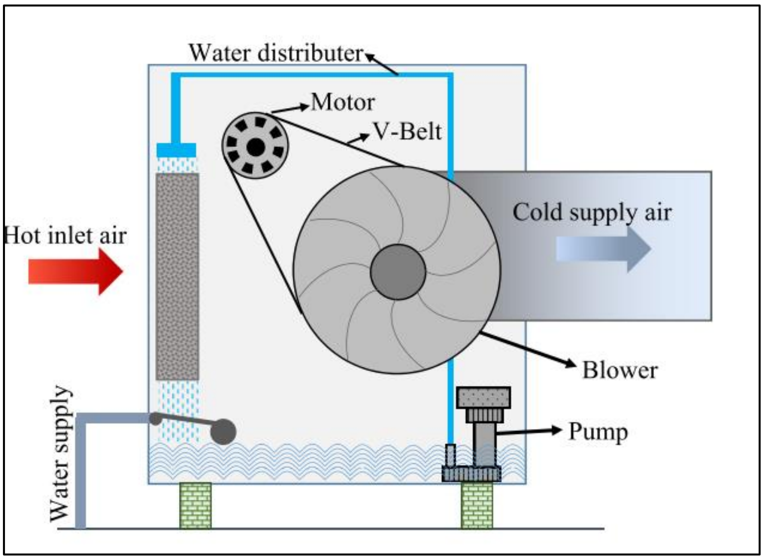


Figure 2.13. Schematic of the investigated direct evaporative cooler (Sohani *et al.*, 2017)

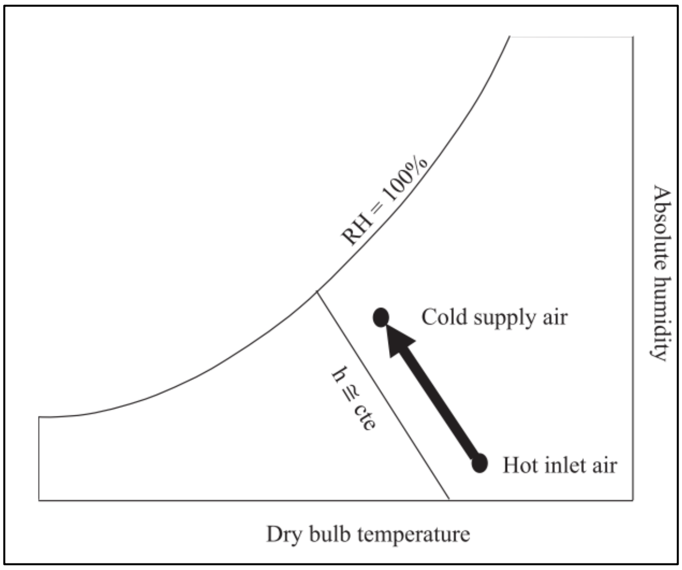


Figure 2.14. Direct evaporating cooling process on the psychrometric chart (Sohani *et al.*, 2017)

Evaporative air conditioning systems are cost effective methods that decrease peak energy demand and have less initial and operational cost (Sohani & Sayyaadi, 2017). Moreover, these environment friendly systems enhance indoor air quality by prevention of pollution emission and humidifying supply air according to indoor air moisture saturation. However, there are also some deficiencies of this system. To control precisely indoor air temperature and ratio of humidity is very difficult in evaporative air conditioning systems. Therefore, it can be appropriate in hot and low humidity climates. In addition, noise is one another problem of it (Jaber & Ajib, 2011).

HVAC

According to study of the National Center for Education statistics about public schools in U.S., indoor air quality is the one of the reported issues for approximately 50% of the public schools. For the productivity of the occupants of the schools, physical comfort should be provided. In order to increase indoor air quality, upgrading is one of the solutions for outdated HVAC systems. According to HVAC system retrofit study of West Hernando Middle School, 40% of energy saving was noted in one-month monitoring. In addition, it is possible to monitor and to analyze data from the buildings with web-based dashboard systems (Thorne, 2018).

2.3.3. Electrical System

Lighting

Lighting consume one-third of electricity consumption of the building. Thus, rational use of electricity is extremely significant (Mahlia *et al*., 2011). Lighting design is also come into prominence because of the role about reducing energy consumption and CO_2 emissions in building and lighting retrofit in building is frequently focused on minimizing the lighting energy consumption. As a result, selection of the proper lamp and luminaries and applying lighting control strategies is indispensable (Şener Yılmaz, 2016). In this respect, although in the lighting market, there are various types of lighting system, choice of lamp that is changed according to task, will be achieve by the lamp and properties of the lamp (Mahlia *et al.*, 2011).

Lighting retrofit is defined as replacing inefficient lamps with efficient ones (Ye *et al*., 2015) and it is also defined as an opportunity for utilizing new technology and techniques to upgrade and redesign the existing lighting system in order to develop lighting condition and decreasing energy consumption (Kromer *et al.*, 1992). Moreover, in case of limited financial conditions, it also effective method for improving energy efficiency and quality of lighting without redesign the entire system (Ciobanu & Pentiuc, 2016).

Dilouie (2011) indicated that although labor and equipment cost remained comparatively stable, the average annual increase in energy price has passed the average rate of inflation over the past 10 years. As a result, the project that not organized for investment about energy efficiency can be changed the periodic evaluations by qualifying in later years (DilLouie, 2011).

The lighting is a business asset that is very critical both built environment and the organization. In addition, this asset is often ignored in the existing building. Upgrading existing lighting system to efficient lighting standard, provide up to 50% cost saving about lighting energy according to National Lighting Bureau. Thus, building owner focused on changing their building lighting system with more energy efficient technologies to accomplish maximum benefit. However, the aim of the lighting is not to obtain minimum wattage and according to its application, lighting should improve task performance, provide visual comfort, reveal form and architecture and attract interest (DilLouie, 2011).

Department of Energy (DOE) indicated that (as cited in Delgoshaei *et al.*, 2017) development of energy efficient lighting fixture and including control strategies such as occupancy and vacancy sensors provides an opportunity to save up 75% and The U.S. Department of Energy (DOE) is promoting research projects for providing high quality and energy efficient generation of Light-Emitting Diode (LED) and Organic Light Emitting Diode (OLED) lighting product. In addition, Interior Lighting Campaign for Better Buildings design to save over $2 billion USD electricity cost annually by upgrading the efficiency of existing lighting fixture (Delgoshaei *et al*., 2017).

There are many alternatives that include various types of lighting technology are measured in terms of visual comfort conditions and lighting energy efficiency (Şener Yılmaz, 2016). In addition, because of the inefficiency of the common lightings such as incandescent, fluorescent and halogen lamps, existing lighting retrofit enables to achieve high efficiency in terms of energy by preferring LED solid-state lighting that has long life-time and low maintenance (Ko *et al*., 2011).

Before the retrofit application, project qualification is significant phase to achieve successful retrofit project. For the initial assessment of retrofit potential, a preliminary screening is used decide if a detailed lighting audit. This preliminary study composes of a quick walkthrough of building for defining the predominant type of lighting equipment and making lighting level measures at some part of the building. In addition, if there is accurate plan and photographs of the building, they also provide quick determination of retrofit project (Benya & Leban, 2011).

In some conditions, it is obvious that retrofit is worthwhile. These conditions are:

•the facility has long hours of operation

•old lighting system that installed before 1990

•the facility has high electricity demand

•the facility has excessive illuminance

•the facility has incandescent lighting

After deciding that retrofit is beneficial for existing lighting system, type of retrofit should be decided. There is various type of retrofit application from simple replacement of light bulbs to changing whole lighting system that includes electrical wiring, socket (Benya & Leban, 2011).

Table 2.3. *Table of lighting retrofit strategies*

Type of Retrofit Strategies	Lighting System Components					
	Electricity Wiring	Controller	Socket Outlet	Light Fixture		
Type 1/ Lighting Fixture Replacement	Constant	Constant	Constant	Renewed		
Type 2/ Partial Change of Equipment	Constant	Constant	Renewed	Renewed		
Type 3/Partial Change of Equipment	Constant	or/and Renewed	or/and Renewed	or/and Renewed		
Type 4/ Complete Change of Equipment	Renewed	Renewed	Renewed	Renewed	+	Smart Metering Control Communication Wireless

According to retrofit examples in the literature, retrofit strategies can be categorized into four main types (Table 2.4.).

Type 1: It is based on simple lighting fixture replacement.

Type 2: It includes renewing lighting system equipment partially. Socket outlets and light fixtures are the changing components of the lighting system. Especially, in office examples, with the change of the suspending ceiling, both sockets and light fixtures is renewed.

Type 3: It is also partial change of equipment. Different type of lighting components can be renewed according to lighting system needs. Utilizing motion sensor in the residential building corridors is an example for Type 3.

Type 4: It includes complete change of equipment. Smart lighting application that controls the energy efficient lighting fixture with intelligent sensors is an example for this type of retrofit, variety of sensors and control technologies integration provide to achieve higher energy efficiency lighting system. Wireless sensors and actuator networks can be used for sensor based intelligent lighting system.

There are many advantages of the lighting retrofit for building owners and the building users. While the direct benefits are related to reducing electricity demand, energy saving and decreasing building operational cost, improved lighting quality, potential increases in productivity are less quantifiable advantages of it (Benya & Leban, 2011).

2.3.4. Architectural Solutions

Design of the physical characteristics of the buildings in terms of form, orientation, envelopes materials and types (such as transparent or solid material), color of the façade and architectural elements for sun protection such as overhangs, blinds, vertical fins, is one of the factors that affect the building energy consumption. In this respect, compactness that can be defined as the suitable proportional relation between building volume, useful area and envelope (compactness direct quotation 'an ability of a building volume to fit as much useful area into the external envelope (the totality of external walls, windows, roof and lower heated floor areas) as possible) is important parameter that should be consider for energy efficiency of the building. Moreover, compactness is not only affecting the energy demand in operational phase, but also the efficiency of the construction and demolition process of the building in terms of energy requirements such as extraction, processing, recycling *etc*. and material quantity.

Although the buildings have the same shapes and volumes, architectural layout characteristics such as number of floors, location and proportion of the heated spaces *etc*. can altered the energy efficiency. In addition, window area and solar transmittance abilities are the other factor that should be considered in terms of compactness due to the effect on energy flow between facility and exterior (Parasonis *et al*., 2012).

2.3.5. Renewable Energy Sources

On demand side, building envelope, electrical system and mechanical system retrofits come into prominence in terms of increasing indoor air quality, proving thermal comfort and reduce energy demand. On the supply side, cutting edge energy conversion and storage technologies like heat pumps and combined heat and power system and renewable energy resources like solar, wind geothermal and biomass technologies become crucial (Donnarumma & Fiore, 2017).

Solar Thermal Energy Systems

Solar Thermal Energy (STE) Systems are one of the renewable energy sources that transforms solar energy into heat energy. With development of the technology, efficiency of the STE systems is improved while reducing cost. In other words, heat storage capacity and durability of the systems are enhanced (Raccurt & Disdier, 2017).

There are two main types of collectors: flat-plate collector and evacuated tube collector. Flat-plate collectors are composed of collectors, flow channels (pipes), circulation pumps and water tanks. In terms of heat loss, flat-plate collectors have some deficiencies because of the gap between the glass cover and heat collecting panel. Significant amount of heat is lost due to the convection and the conduction of air in the gap. Especially in winter season, system can be damaged because of freezing. Unlike flat-plate collectors, tube collectors are well insulated. In addition, tube collectors are highly efficiency in terms of heat collecting (Zhou *et al*., 2018).

Although, STE systems are available in daytimes, heating energy demand can reach the peak point in the evening. Mismatch between energy source and demand can be solved with seasonal solar thermal energy storage (SSTES) systems (Ma *et al.*, 2019). In addition, phase change materials (PCM) such as organic paraffins and inorganic salts can store the latent heat during daytime (Touati *et al.*, 2017). PCM also provide temperature balance of the water in tube collectors by storing excess heat. Therefore, thermal storage capacity of the system can be increased without any extra storage volume (Zhou *et al*., 2018).

Solar Electricity Equipment

Energy demand is increasing day by day due to many reasons such as population growth, technological developments, industrialization, comfort of people *etc*. and the difference between production and consumption is opened day by day. Therefore, solar energy is one of the renewable energy sources that the buildings can benefit from. The buildings designed to benefit from the sun can be used with passive methods and it is also possible to use sun energy with active systems that are added or integrated into the building. Photovoltaic (PV) solar cell, one of active systems, is device that convert sunlight directly into electrical energy. The word "photovoltaic" comes from the combination of the word "photos" and "voltaic" from Alessandro Volto, the pioneer of electricity (Sayın & Koç, 2011).

PV system consist of five main components: PV modules, inverters (converters), battery, charge control units and other system components. PV modules are the most important part of the system. PV cells are produced from semiconductor materials that generate electricity with the energy they receive from the sun. These cells, which are thin enough to be measured by micrometer, are generally square, rectangular or circular and their area is around 100cm^2 (Sayın & Koç, 2011).

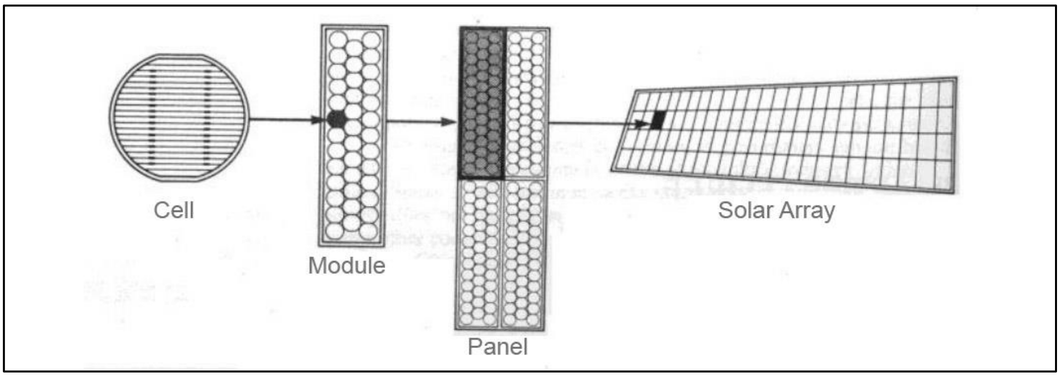


Figure 2.15. Photovoltaic cell, module, panel and solar array (Çelebi, 2002)

The energy obtained from a single PV cell is relatively small. For this reason, the cells have connected each other in order to create modules. The panels are also generated by the combining of the modules. To generate large amounts of electricity, the panels are connected to each other to form a solar PV array as show in Figure 2.15. that is translated from Turkish (Çelebi, 2002). Typical PV module consist of three main layers from back to front respectively: PET (poly ethylene terephthalate) film, PV cell and PET film or glass (Figure 2.16.) (Sayın & Koç, 2011).

PV panels, one of the clean energy sources, is increasing with development of the technology and increasing efficiency of the systems. However, energy demand is not only during daytime, but also peak energy load is generally generated in evening period for some types of buildings. Thus, combination of PV system with battery storage is the requirement to meet the energy need in evening. However, high-capacity battery storage generates additional cost for hybrid PV systems. Therefore, hybrid energy storage systems, which are designed to meet the daily energy needs, can reach the optimum level in terms of performance and cost (Hafız *et al.*, 2018).

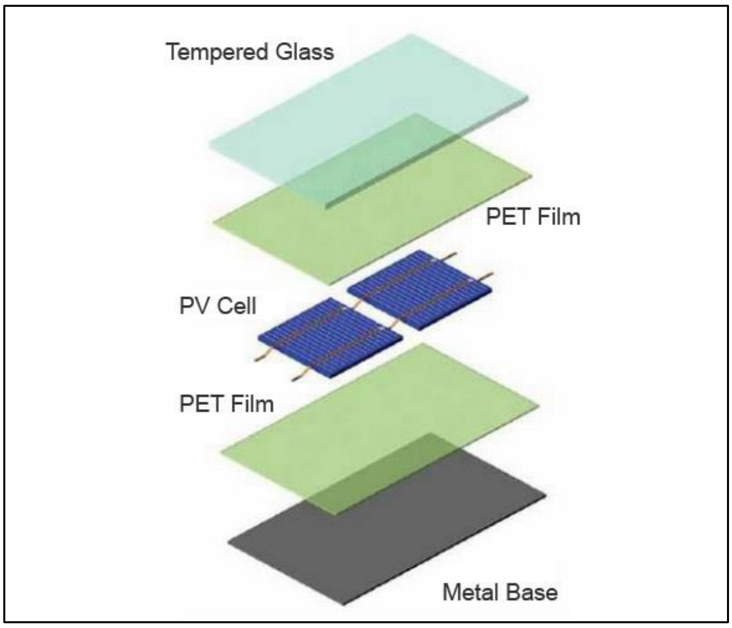


Figure 2.16. A typical PV module structure (as cited in Sayın & Koç, 2011)

Monitoring of produced energy is very critical issue for increasing number and size of PV panels. Because, the performance of the same panels can vary considerably due to many factors. For example, geographical location and position of panels are the main factors that affect amount of energy produced due to the variation of the irradiance. In addition, local weather condition like cloud intensity can cause unpredictable amount of energy production. Even if the PV panels are the same location or side by side, elements such as trees, buildings *etc*. in the nearby environment are other factors that affect the energy production performance (Huuhtanen & Jung, 2018). Another factor that reduces the efficiency of PV panels is surface contamination. The effect of this pollution, which is due to environmental factors, decreased the performance of the module by 3.5% in a study (as cited in Sayın & Koç, 2011). Therefore, the location where the PV module is installed should be suitable for cleaning its surface (Sayın & Koç, 2011). In addition, roofs are preferred as the place for the installation of PV panels. However, in the literature, there are researches about the PV panels that can be installed on south-facing facades (Zogou & Stapountzis, 2011).

Because of the energy performance variation of PV panels, electrical power production is generally monitored based on data from the sensors connected to the PV panels. In typical monitoring systems, time-power curves of electrical power production can be generated and visualized. Thus, in the literature, there are some studies related to predictive maintenance of PV panels (Huuhtanen & Jung, 2018).

Utilizing renewable energy systems has been growing recently. Installation of this non-polluting energy resources is promoted by government agencies with funding and tax reduction. Thus, decision about PV panels energy production capacity and installation location is important decisions that should be analyzed in detail (Karoui *et al*., 2018).

2.4. Effects of the Climate Characteristics on Sustainability

Climate is one of the main factors affecting the energy performance of buildings. As the weather conditions directly affects the indoor environment and increasing or decreasing this temperature to the comfort conditions lead the amount of energy consumed for the heating requirement. Therefore, the climate characteristics should be analyzed in detail and the result of this analysis should be considered in decision making process of energy retrofit strategies to be applied (AlFaris *et al.*, 2016).

The proposed technologies and solutions for energy efficiency of the building differ according to the climate type. For example, low thermal transmittance of doors and windows is proper for cold climate regions and it is recommended to use sun shading devices on building facades for hot-humid climate. In other words, the compatibility of proposed systems and technologies to climate of building should be considered for achieving energy efficiency (Liu & Ren, 2018).

For example, there are many studies in the literature that the optimum thickness is different for each climate type (Özkan & Onan, 2011) (Çomaklı & Yüksel, 2003) (Gölcü *et al.*, 2006). In addition, Aktemur and Atikol (2017) have been carried out to determine the optimum insulation thickness, which varies according to climate characteristics, material types and energy resources. According to these studies, it is noted that climate and the amount of energy consumption affects the optimum thickness of insulation (Aktemur & Atikol, 2017).

In the literature, there is also research of Mutlu on the sustainability of the systems chosen for heating requirement in different climates. According to this study, it has been determined that AC systems are more effective in high temperate climates, whereas in cold regions, natural gas is more sustainable than heat pump. In addition, it is stated that outdoor air temperature affects the performance of the coefficient and climate has a significant impact on the sustainability of buildings (Mutlu, 2018).

Energy retrofit is one of the approaches required to ensure energy efficiency of buildings and reduce CO_2 emissions. It is possible to use the potentials of the buildings in terms of energy efficiency with a correct retrofit plan. However, the same retrofit plan does not show the same energy performance in different climates. As a result, climate specific retrofit scenarios need to be created and the feasibility of these scenarios should be studied. Thus, potential energy savings of retrofit plans are better understood and guided by decision makers (Yao *et al.*, 2016).

The suggestion of feasible retrofit measures is a priority for type building project and it will guide the decision makers in the retrofits, which will be done in large numbers.

Retrofit strategies specific to climate type can be encouraging for investors because of their high energy saving potential and, cost-optimal level of building can be defined according to climates. In addition, it is very important that standards such as TS825, the guide for buildings, meet the requirements of cost-optimality. According to climates, there should be a consistency between building standards and energy performances. In addition, according to Ashrafian Touraj *et al* (2016) studies, the standards proposed by TS 825 for cold climate are weak and provide low energy and cost performance (Ashrafian *et al*., 2016).

2.5. Critical Analysis of Literature Review

Proving sustainability in school building has great importance in the reviewed literature. There are many studies in the literature related to energy efficiency, sustainability, energy retrofit measures, existing buildings and school buildings renovation projects. In this study, a detailed research has been done in the scope.

Many sources have been found in the literature regarding the importance of the sustainability of school buildings and general information about techniques that can be applied to improve sustainability in school building. In these studies, specific projects were studied, and analysis results of these projects were presented.

In the literature, the importance of sustainability and energy efficiency is underlined. It stated that energy efficiency and sustainability should be provided not only in new buildings, but also in existing buildings. In addition, it is also reported that energy retrofitting for many existing buildings is a requirement to increase sustainability. Moreover, there are numerous studies in the literature to determine the appropriate retrofit strategy for buildings and to ensure an optimum relationship between energy efficiency and cost.

Existing approaches include analyzes based on specific climates for specific buildings. In the literature, only a few studies focus on the retrofit scenarios that can be applied in different climates. However, only energy efficiency is emphasized in these studies.

In addition, sustainable impact of retrofit measures is studied only in the study of Jafari and Valentine (Jafari & Valentin, 2017). However, in this study, it is not stated that these retrofits have different sustainability effects in different climates.

In other words, there is no study in the literature that retrofits have an impact not only on energy efficiency but also on sustainability and this sustainability effect can vary in different climatic regions.

In this study, it is aimed to study the sustainability effect of retrofits in different climates considering these gaps in the literature. As a case study, type school project that were built in different climatic regions across the country with low energy performance, is selected. Thus, a study that evaluate the sustainability effect and climate parameters for retrofit types was aimed.

CHAPTER 3

MATERIAL AND METHOD

In this chapter, the materials and methods of thesis are explained. Firstly, proposed sustainability assessment technique is explained. After, materials of this study are determined, and detail information related to selected materials are given in the data collection section. In addition, case studies that are necessary for evaluation of the hypothesis, are defined. At the end of this section, general overview related to case studies and the research hypothesis are generated.

3.1. Sustainability Assessment Techniques

There are many different sustainability assessment techniques as mentioned in previous chapters in terms of economic, environmental and social aspects.

In the research study of Jafari and Valentine, while the amount of greenhouse gases emission is used to measure the effect of energy retrofit measures on ecological sustainability, the effect on economic sustainability is calculated with payback period analysis. In addition, with the survey on building academic researchers, social sustainability of retrofit measures is evaluated.

In this study, to measure the sustainability effect of retrofit types implemented to school building in different climates, sustainability measurement methods in the study of Jafari and Valentine are used, and it is aimed to evaluate the relationship between the concepts of climate, retrofit measures and sustainability (Jafari & Valentin, 2017).

Therefore, economic sustainability is measured with payback analysis based on product cost, labor costs and discount rate. Ecological sustainability is evaluated by decreasing the released amount of CO_2. At the same time, the effects of retrofit studies on productivity, health and comfort factors were evaluated and social sustainability is assessed with the survey on educators about social sustainability of retrofit measures. Consequently, the sustainability effect is defined as the sum of economic, environmental and social sustainability.

3.2. Material Selection

In this part, because of the purpose of this study, information related to type 735 school project, the proposed energy retrofit measures and climate types in Turkey are given.

3.2.1. Type 735 School Building

In this research, type 735 school buildings that has been built many times before the year 2000 with some minor changes all over the country, was selected as a case study.

Based on the interview it became clear that an energy retrofit strategy for type 735 school building was proven to be very important as it would serve as an example for schools across the country. In addition, how the Ministry has proceeded to improve the existing school structures was better understood. According to the information provided in this meeting, currently two different types of retrofit are conducted at schools in Turkey: 'maintenance and repair' ('bakım onarım' in Turkish) and 'large repair' ('büyük onarım' in Turkish).

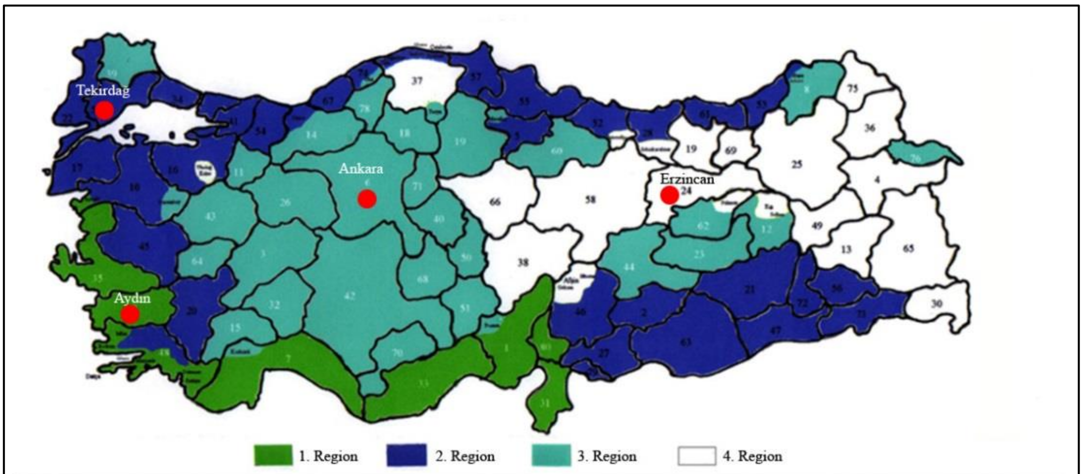
The maintenance and repair expenses cover the small-scale activities such as paint, whitewash *etc.* which are required to be done annually. Large repair costs are long-term modifications. Such as exterior thermal sheathing and insulation works, renovation the mechanical systems of school buildings, structural reinforcement *etc.*

The Ministry of Education has a limited budget for large repair costs. Therefore, deciding for which retrofit types this budget will be spent is another problem in large scale repair planning. In addition, according to another information received from the Ministry, it is stated that the works carried out within the scope of large repairs are similar for the type projects and the same type of retrofits are applied to same type school projects. However, it was stated that the location of the school building, building orientation and climate type were not taken into consideration and no feasibility study based on the location was made in the determination of these retrofitting plan. Furthermore, it has been stated that the Ministry of Education attaches importance to energy efficiency through pilot projects carried out in recent years.

As a result, energy retrofit is a necessity for school projects built between 1950 and 2000 throughout the country. In retrofit projects that are planned to be implemented for such type school buildings, it is important to consider the location of the project and the climate zone of project location in terms of energy efficiency and sustainability. Therefore, it is necessary to prepare retrofit plan according to the climate region of the project location, since the same types of retrofits that can be proposed for each climate region will have different impact on energy efficiency and sustainability.

Therefore, proposed retrofit strategies according to climate characteristic provide to maximize the potential impact of overall energy saving. To examine potential of the energy retrofits in different climate, four cities in four climatic regions determined by TSE (Figure 3.1.) (Turkish Standards Institute, 2009) and type 735 school projects in these provinces were decided. These schools, and their climate zones are listed below and shown in the (Figure 3.1.):

- Climate Region I: Aydın, Adnan Menderes Anatolian High School (Figure 3.2.)
- Climate Region II: Tekirdağ, Süleyman Paşa Kadriye Nazif Gölge Vocatonal and Technical Anatolian High School (Figure 3.3.)
- Climate Region III: Ankara, Ayrancı Anatolian High School or Ayranci Anatolian High School (Figure 3.4.)
- Climate Region IV: Erzincan, Erzincan Atatürk Vocational and Technical Anatolian High School (Figure 3.5.)



01- ADANA	10- BALIKESİR	19- ÇORUM	28- GİRESUN	37- KASTAMONU	46- K.MARAŞ	55- SAMSUN	64- UŞAK	73- ŞIRNAK
02- ADIYAMAN	11- BİLECİK	20- DENİZLİ	29- GÜMÜŞHANE	38- KAYSERİ	47- MARDİN	56- SİİRT	65- VAN	74- BARTIN
03- AFYON	12- BİNGÖL	21- DİYARBAKIR	30- HAKKARİ	39- KIRKLARELİ	48- MUĞLA	57- SİNOP	66- YOZGAT	75- ARDAHAN
04- AĞRI	13- BİTLİS	22- EDİRNE	31- HATAY	40- KIRŞEHİR	49- MUŞ	58- SİVAS	67- ZONGULDAK	76- IĞDIR
05- AMASYA	14- BOLU	23- ELAZIĞ	32- ISPARTA	41- KOCAELİ	50- NEVSEHİR	59- TEKİRDAĞ	68- AKSARAY	77- YALOVA
06- ANKARA	15- BURDUR	24- ERZİNCAN	33- İÇEL	42- KONYA	51- NİĞDE	60- TOKAT	69- BAYBURT	78- KARABÜK
07- ANTALYA	16- BURSA	25- ERZURUM	34- İSTANBUL	43- KÜTAHYA	52- ORDU	61- TRABZON	70- KARAMAN	79- KİLİS
08- ARTVİN	17- ÇANAKKALE	26- ESKİŞEHİR	35- İZMİR	44- MALATYA	53- RİZE	62- TUNCELİ	71- KIRIKKALE	80- OSMANİYE
09- AYDIN	18- ÇANKIRI	27- GAZİANTEP	36- KARS	45- MANİSA	54- SAKARYA	63- ŞANLIURFA	72- BATMAN	81- DÜZCE

Figure 3.1. HDD regions identified by TS 825 in Turkey (Turkish Standards Institute, 2009)

Figure 3.2. Aerial view, location and orientation of Aydın Adnan Menderes Anatolian High School (Source: "Aydın, Adnan Menderes Anatolian High School", 37°50'43.41''N, 27°49'48.57''E. Google Earth. 07/27/2018. Accessed: 03/20/2019.))

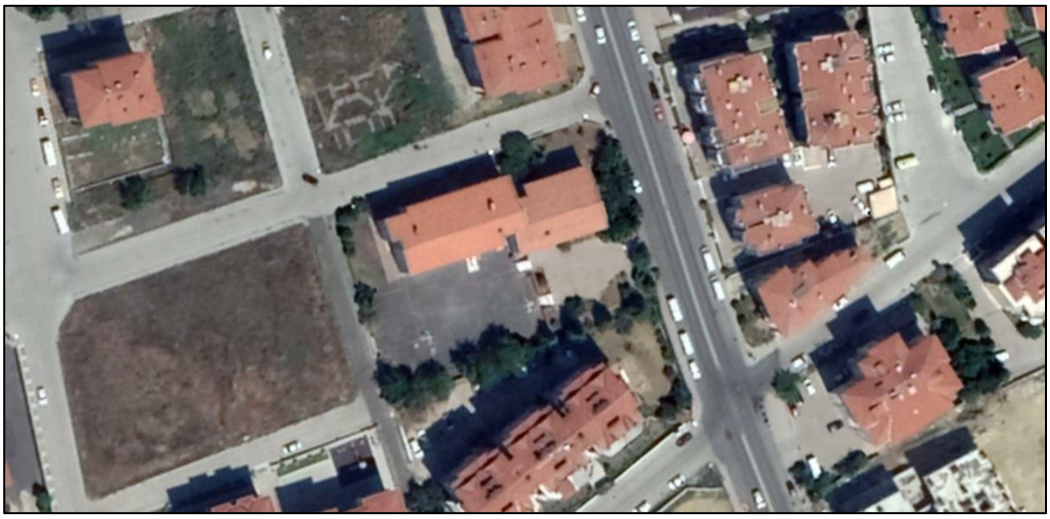


Figure 3.3. Aerial view, location and orientation of Tekirdağ Süleyman Paşa Kadriye Nazif Gölge Vocational and Technical Anatolian High School (Source: "Tekirdağ Süleyman Paşa Kadriye Nazif Gölge Vocational and Technical Anatolian High School",40°57'41.71''N, 27°29'19.92''E. Google Earth. 08/04/2017. Accessed: 03/20/2019.)

Figure 3.4. Aerial view, location and orientation of Ayrancı Anatolian High School (Source: “Ayrancı Anatolian High School”, 39°53’18.33’’N, 32°50’51.04’’E. Google Earth. 09/24/2018. Accessed: 28/04/2019.)

Figure 3.5. Aerial view, location and orientation of Erzincan Atatürk Vocational and Technical Anatolian High School (Source: “Erzincan Atatürk Vocational and Technical Anatolian High School”, 39°44’30.05’’N, 39°30’19.55’’E. Google Earth. 09/24/2018. Accessed: 03/20/2019.)

The selected high schools in Ankara and Aydın were established in 1996 and 1992 respectively. However, the date of establishment of high schools in Tekirdağ and Erzincan is not clear, but it is known to be before 2000 based on the interview with Ministry of Education.

In this research study, Ayrancı Anatolian High School in Ankara, was selected as a case study and a site trip was organized on March 14, 2019. Ayrancı Anatolian High School was built on public land in Hoşdere Street No: 139 in Yukarı Ayrancı neighborhood of Çankaya district, of Ankara province (Ankara Ayrancı Anadolu Lisesi, 2019). The school has a large garden on the front side.

Brief information about the school is listed below:

- The construction year of the school buildings is 1996;
- Current number of students is 698;
- Total number of classrooms is 24, including a computer laboratory and 2 laboratories;
- Total area of the construction is 3240 m²;
- The building consists of two main blocks on different levels that connected to each other with core containing a staircase and sanitary facilities. Each of block has 4 main floors (including the basement floor);
- The school also includes of a library and cafeteria.

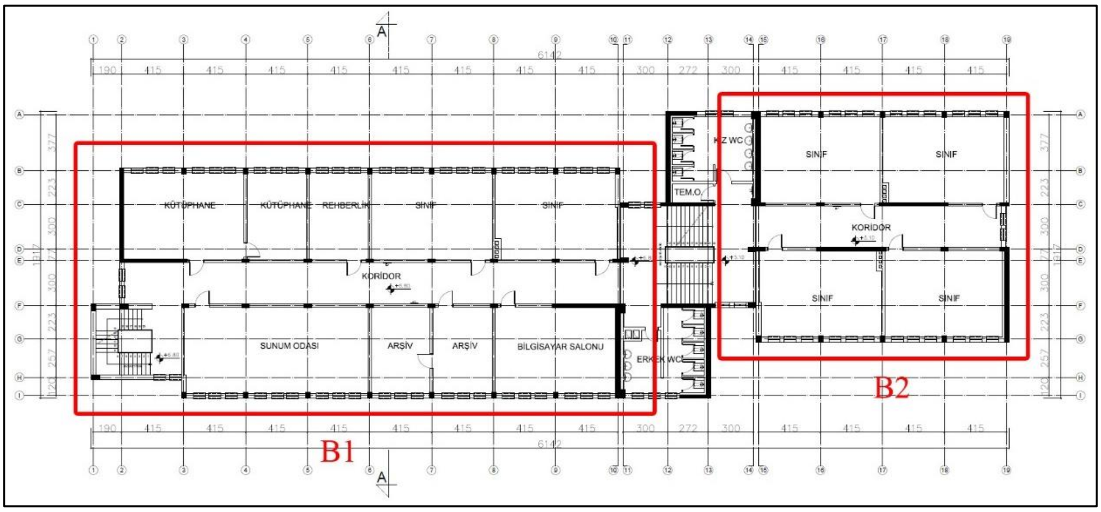


Figure 3.6. Typical floor plan with marked two blocks: B1 and B2

Figure 3.7. West façade of Ayrancı Anatolian High School in Ankara

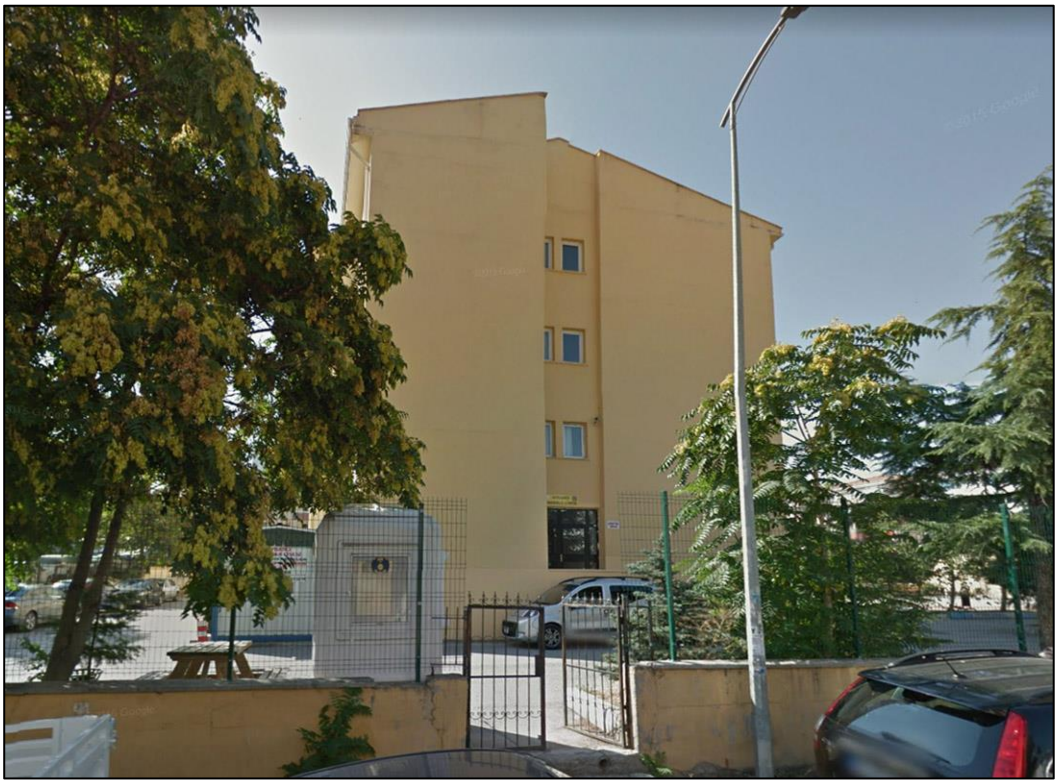


Figure 3.8. North façade of the school building

External Walls and Structure of the Building

According to plan and site photographs, East-West elevations of the building and South-North elevations has a substantially equal number of windows openings. In addition, South-North elevation of the building has only a few openings.

According to site visit, it is detected that the school building has been constructed as concrete frame building with block infills. Moreover, on the short facades of the building (North and South facades), there are shear walls. (Figure 3.8.) In addition, external walls of the building have no thermal insulation layer and base of the ground wall is concrete without any thermal and waterproofing layer.

Roof and Floors

The building has pitched roof that forms a cold and unoccupied roof space. Top of the roof is covered with board and tiles. In addition, at the top of the concrete slab of the unoccupied roof space and there is no insulation layer.

According to observation and measures, the building consists of 20cm thick concrete slabs. While in wet spaces, floor finish is tile; in other space, floor finish is terrazzo. In addition, at the ground floor slab, it is expected that there is also no thermal insulation.

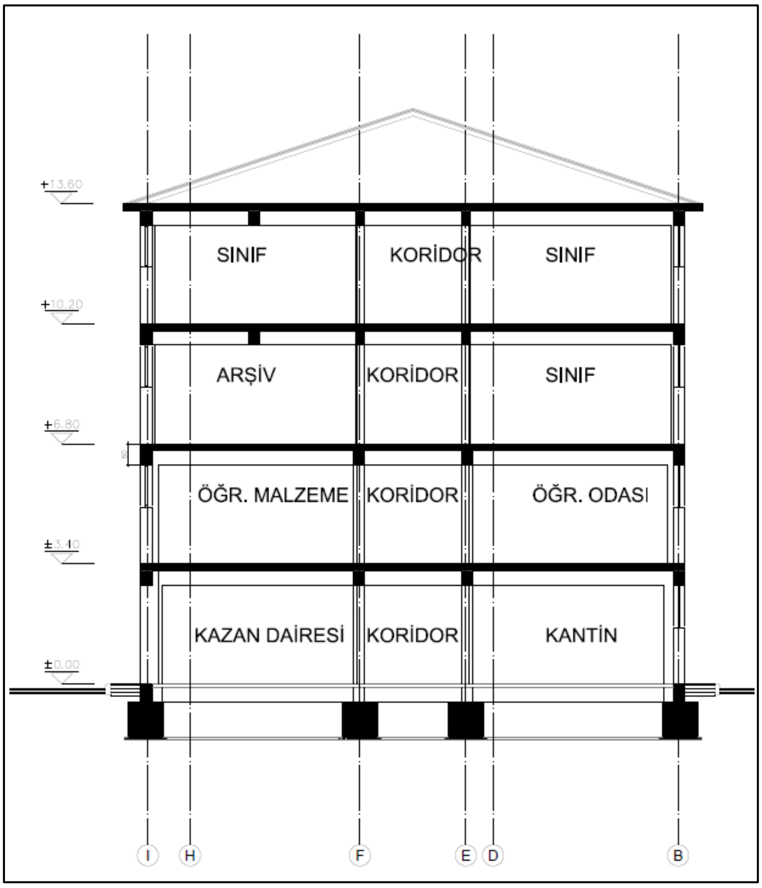


Figure 3.9. Section of the school building

Doors and Windows

In the building, there are two external doors on West façade. They provide the entrance for B1 and B2 blocks. Doors are metal framed doors with single glazing. Windows of the building is PVC framed with double glazing. At West and East façades, windows have same dimensions and was placed in groups of three (Figure 3.10.). Although, the longest façades of the building are west and east façade, there are no sun shading devices or glare control on these facades.

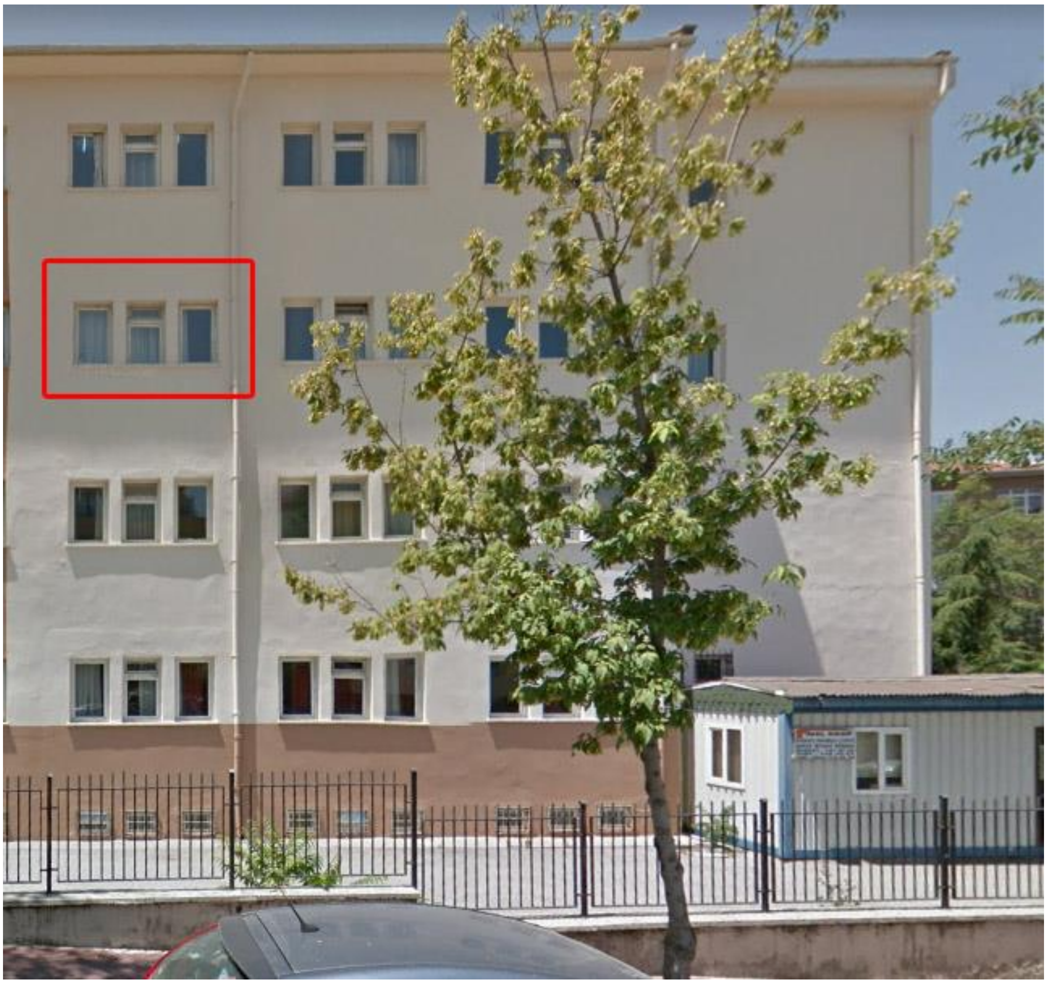


Figure 3.10. PVC framed double glazed window group

Lighting

Lighting system constitutes major part of the electrical energy consumption of the school. In the existing lighting system of the school surface mounted fluorescent lamps were preferred. Each classroom has 8 fluorescent lamp fixtures. Technical specification of the lighting equipment is shown in Table 3.1.

Table 3.1. *Existing Lighting Fixture Specifications*

Existing Fixture	
Power (W)	36
Lumen Output (lm)	2500

Heating and Ventilation

The school heated by boiler fired with natural gas. In addition, in heating system tubular radiators was installed and heating distribution pipes partially insulated.

Each classroom in the school have 6 windows in two groups of 3. All the window can be opened for ventilation.

In the school building, there is no a central hot water system. Therefore, in WCs and other spaces, cold water is supplied. In the kitchen of the canteen, electric kettle is used for hot water

Energy Modelling

In this study, in order to evaluate the impact of retrofit types applied to existing school buildings on sustainability, baseline energy model of existing four school buildings in different climatic regions were prepared and the physical characteristics of Ayrancı Anatolian High School building were taken as basis for these energy models. It was assumed that this school building have the same physical conditions and orientation in each climatic region.

A field trip to the aforementioned school was conducted to gather a relevant data from from the existing school. In the light of the information obtained during the field trip, the baseline energy model of the existing Type school project in Ankara was prepared using the Design Builder software. (Figure 3.11.) Design Builder is an Energy Plus based software tool designed to measure and control performance in terms of energy, carbon, lighting and comfort. Energy Plus is a building energy simulation program developed by the US Department of Energy to model building heating, cooling, lighting, ventilation and other energy flows. In addition, Design Builder allows to combine three-dimensional building modeling with dynamic energy simulation (Design Builder, 2019).

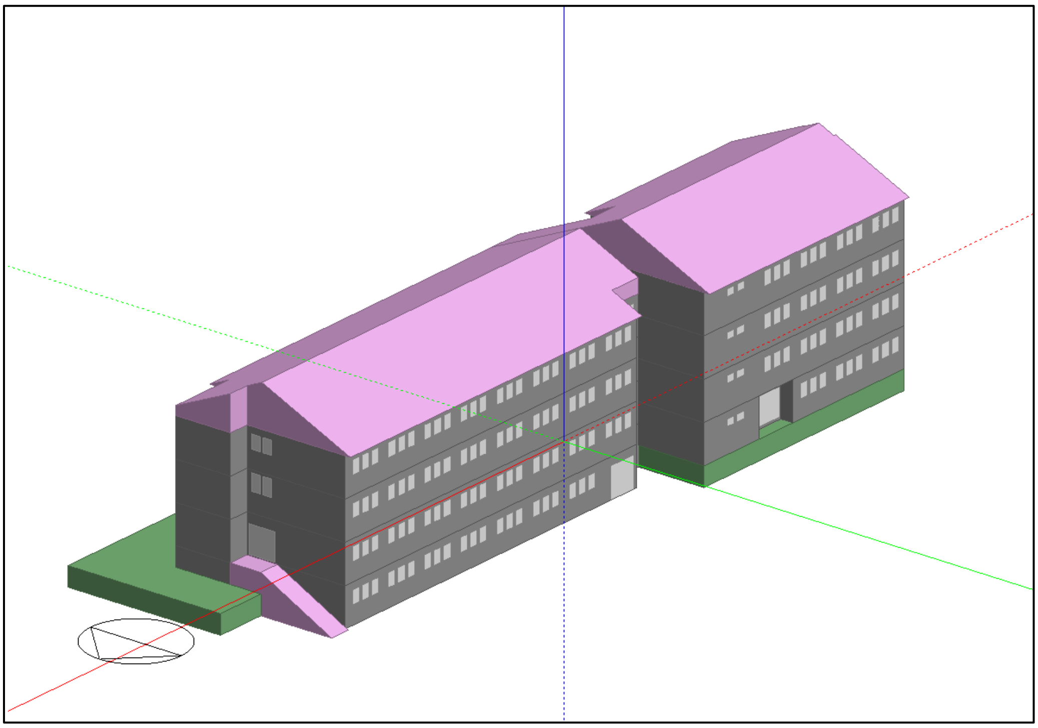


Figure 3.11. Existing building energy model in Design Builder Software

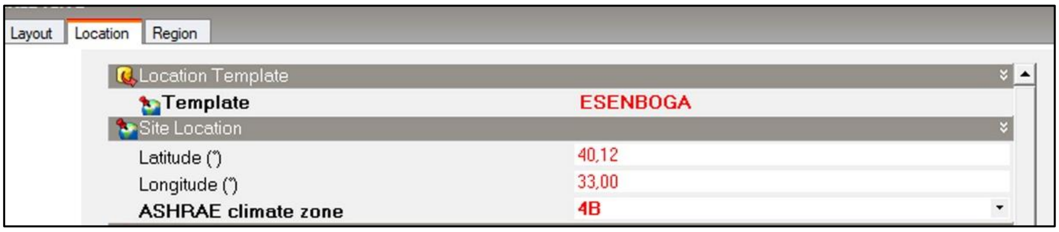


Figure 3.12. Energy model location data of buildings in Ankara

While preparing the energy model of the existing type school building in Ankara, 4B ASHRAE climate zone and 'Esenboğa' location template was selected for defining of location data. (Figure 3.12.)

The energy model layout of the existing building was modelled in accordance with the information obtained during the field trip. In this baseline energy model, the exterior walls of the building were defined as 25cm thick brick wall and 3cm thick cement-based plaster layer is defined on the inside and outside of this wall. In addition, the interior slabs and flat roof slab were defined as uninsulated 20cm cast in place concrete and interior slabs also have 7cm thick screed and 3cm terrazzo covering layers. The building roof type was assigned as an unoccupied pitched roof. Since, there is no detailed material information about the roof structure, template that is named pitched roof with wooden structure was assigned for the roof. According to this template, the roof layers were assumed to be 25mm thickness clay tiles on 20mm air gap and 5mm roofing felt materials.

During the field trip, it was observed that the existing building had double glazed PVC framed windows. Therefore, PVC framed windows with 6mm clear glasses were defined as existing building energy model openings.

While the lighting system of the existing structure was defined in the energy model, T5 Fluorescent lamp (25mm diam, 36W) was chosen as existing lighting fixture. There are 8 units in each classroom (46m^2) and 300Lux light levels is targeted according to ASHRAE 90.1 standards in the classrooms. Based on this information, the normalized power density is calculated as 2.0869W/m^2-100lux and this information is transferred to the energy model.

As the heating system of this energy model, a template named radiator heating and boiler fired with natural gas, was assigned. In terms of heating requirement, the school building was categorized into three main area types: classrooms and offices (1), circulation areas (2) and unused spaces (3). The heating set point was fixed at 21°C for the classrooms and offices and 15°C for the circulation areas. Unused areas such as storage and technical areas are defined as unheated areas. (TMMOB, 2015)

In addition, natural ventilation template was assigned as a ventilation system. Thus, it is assumed that users open windows every day at certain time intervals. The air flow rate within this period was assumed to be 5.00 (ac/h). The occupancy period assigned according to the user period was determined to be between 8 AM and 6 PM on weekdays, excluding holidays.

As a result, the energy model of the existing school building in Ankara has been completed. After that, the location and climatic information of the prepared energy model were changed to Aydın-3A Climate Zone, Tekirdağ-3C Climate Zone and Erzincan-5A Climate Zone and these models are recorded separately to prepare the energy models of the existing school buildings in Climate Region I, II, III and IV.

Table 3.2. *The amount of existing building energy consumption in different climate regions*

Climate Regions	Heating (kWh)	Lighting (kWh)	Energy Consumption Per m^2 (kWh/m^2)
1.Region-Aydın	60,885	13,600	23
2.Region-Tekirdağ	107,027	14,211	37
3.Region-Ankara	191,937	13,680	63
4.Region-Erzincan	214,585	13,760	70

The energy analysis of the energy models of the existing school buildings in the four different climatic regions was prepared and the calculated energy consumption amounts are shown in the table below. (Table 3.2.)

According to these calculations, the energy consumption required for the maximum heating is in the Climate Region IV and at least in the Climate Region I. The amount of energy spent for heating requirement from Climate Region I to Climate Region IV is increasing. The minimum energy requirement for lighting is in the Climate Region I where the amount of average sunshine duration is the highest. The highest lighting requirement is calculated for the Climate Region II, where the amount of average sunshine duration is the least. (Table 3.18)

In addition, based on the energy analysis, the ratio of energy consumption in school buildings is shown in the Figure 3.13. According to this figure, heating energy consumption for each climate zone is more than lighting energy consumption.

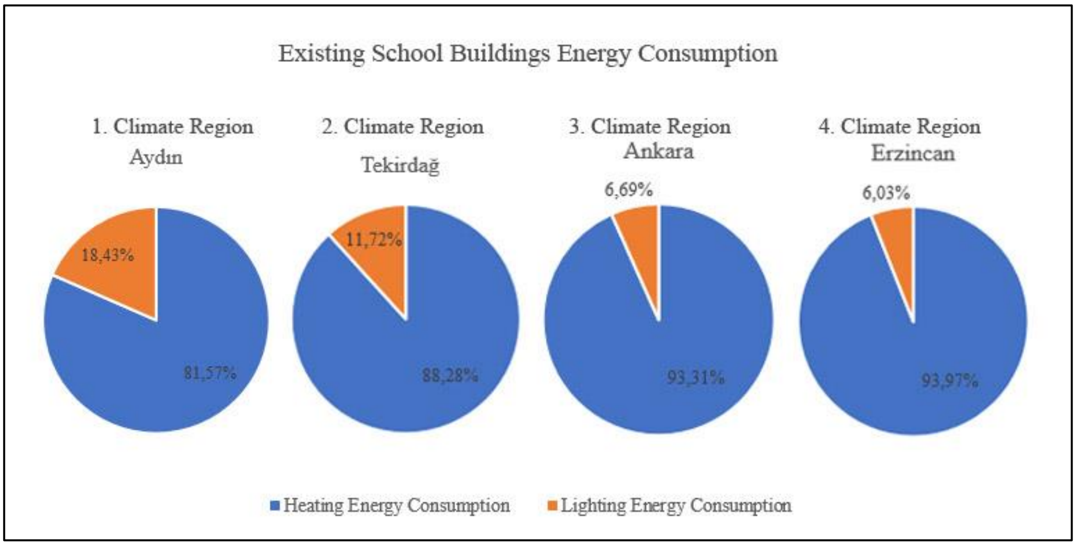


Figure 3.13. Existing school building energy load profile

In addition, to ensure the accuracy and reliability of the calculated energy consumption amounts, a comparison was made with the energy consumption amounts of another school project in Kırıkkale in the GIZ report. (GIZ, 2018) In this report, the amount of energy consumption per m^2 in the school project is calculated as 82 kWh / m^2a. As a result, it was found that the calculated energy consumption amounts were close to similar school projects. (Table 3.2.)

3.2.2. Proposed Energy Retrofit Strategy

There are many retrofit strategies that can be applied to reduce energy consumption and to improve sustainability of buildings. In addition, there are many sources in the literature that evaluate the retrofit strategies in terms of economic sustainability and environmental sustainability. In this study, considering the advantages and disadvantages of the existing school buildings, retrofit types that are implemented to the type 735 school project was decided.

Retrofit Type 1: Envelope Insulation

Based on the interview with Ministry of Education about the school buildings, it was stated that the main energy consumption of the existing school buildings is caused by the heating requirement. Therefore, building envelope insulation is proper retrofit type enables to decrease the amount of energy consumption for heating requirement.

Based on the interview with Ministry of Education, prototype 735 project is built in 1990s and there is no thermal insulation layer used for external envelope. In addition, according to information received during the interview, it has been understood that the same type of retrofit was recommended for type school buildings across the country. During this interview, it was also stated that XPS insulation boards are generally used in the school buildings for exterior wall insulation and blanket type rockwool insulation materials are preferred for the pitched roofs.

In recent years, building envelope insulation has been implemented to school building. According to information received during the site trip organized on March 14, 2019 to Ayrancı Anatolian High School, it is determined that there is no thermal insulation on the exterior facades of the building. Therefore, building envelope retrofit is a necessity for minimizing the heating energy consumption. Moreover, performance evaluation of this retrofit type in different climate regions can be important guide in determining the retrofit types to be preferred according to climate. For this reason, it has been decided to implement thermal insulation to the external wall of the buildings and on top of roof slab in the unused roof space. Considering the isolation materials preferred by the Ministry of Education for schools, while XPS insulation boards with 5 cm thickness is selected as insulation material of the external walls, blanket type rockwool is also preferred for the roof part. In the Table 3.3. and Table 3.4., technical specifications of the selected material are presented.

Table 3.3. *Proposed exterior wall insulation material characteristics-XPS Foamboard (Source: http://www.izocam.com.tr/. Accessed: 10/05/2019.)*

XPS Foamboard	
Thickness(mm)	50
Width (mm)	600
Length (mm)	1200
Heat Conductivity Factor (W/mK)	0.3

Table 3.4. *Proposed roof floor insulation material characteristics-Rockwool Blanket (Source: http://www.izocam.com.tr/. Accessed: 10/05/2019.)*

Rockwool Blanket	
Thickness(mm)	100
Width (mm)	1200
Length (mm)	6000
Heat Conductivity Factor (W/mK)	0.35

In order to evaluate the performance of envelope insulation in each climate region, the above-mentioned envelope isolations were applied to the energy models of the existing structures prepared for four different climate zones. In the preparation of these energy models, XPS insulation (5cm thickness, 0.3 W/mK heat conductivity value) and rockwool blanket (10cm thickness, 0.35 W/mK heat conductivity value) layers were added to the outer surface of the exterior walls of the building model and the upper surface of the roof slab, respectively.

Energy analysis of the school buildings energy models in which envelope insulation was adapted was carried out by Energy Plus that is the energy simulation engine of the Design builder program. The values obtained as a result of these energy analysis are shown in the Table 3.5 below in comparison with the energy values of the existing buildings. According to this table, in the Climate Region IV where the average annual temperature is the lowest among the climatic zones, the annual energy saving amount provided by envelope insulation is the highest (74,975 kWh), while the energy saving amount is the least in Climate Region I which has the highest annual average temperature (19,301 kWh). (Table 3.5.)

Table 3.5. *The energy consumption of envelope insulated energy models in different climate regions*

Climate Regions	Energy Consumption (kWh)		
	Existing	Proposed	Saving
1.Region-Aydın	60,885	41,584	19,301
2.Region-Tekirdağ	107,027	68,949	38,078
3.Region-Ankara	191,937	125,624	66,313
4.Region-Erzincan	214,585	139,610	74,975

In addition, according to TSE, the maximum recommended thermal conductivity values (U value) are given in the Table 3.6. According to Design Builder energy model data, while the U value of the existing school building external walls is 1.7 W/m^2K, the U value of the insulated exterior wall with 5cm thickness XPS board is equal to 0.44 W/m^2K. (Turkish Standards Institute, 2009)

Table 3.6. *U values recommended to be accepted as maximum value in climate regions (Turkish Standardization Institute, 2009)*

Climate Regions	U_W (W/m^2K)
1. Region	0.70
2. Region	0.60
3. Region	0.50
4. Region	0.40

According to Table 3.6., U value of the external wall with 5 cm thick XPS insulation is enough for the Climate Regions I, II and III. However, it is not proper for the Climate Region IV. Since, the recommended value for Climate Region IV is 0.40 W/m^2K and it is below 0.44 W/m^2K. In addition, the recommended U values for the Climate Regions I, II and III respectively are 0.70, 0.60 and 0.50 W/m^2K, and these values are above 0.44 W/m^2K. Therefore, 5 cm thick XPS insulation is suitable in the Climate Regions I, II and III according to TSE for type 735 school building. (Turkish Standards Institute, 2009)

According to the calculations, 1681 m^2 XPS foamboard and 823 m^2 rockwool blanket type insulation are needed for envelope insulation of the existing school building. The minimum, maximum and most likely cost information obtained from the related companies are as follows respectively: 75,505 TL, 110,806 TL and 95,677 TL. (Table3.7.)

Table 3.7. *Envelope Insulation Cost*

Retrofit 1- Envelope Insulation Cost (TL)	
Minimum Cost	75,505
Most Likely Cost	95,677
Maximum Cost	110,806

Retrofit Type 2: Lighting Retrofit

One of the important conditions that should be provided in terms of efficiency and health in schools is to provide appropriate lighting. Daylight sometimes does not enough for providing proper lighting environment for learning activity and in these cases, daylight should be supported by artificial lighting. In this respect, lighting system preferences is extremely important in terms of lighting environment quality and energy efficiency.

In this study, it has been proposed to replace the existing lighting fixture with energy efficient and higher luminous flux. Selected lighting fixture and its specifications are presented in Figure 3.14. and Table 3.8.

Figure 3.14. Proposed T8 Led Tube Lighting Fixture

Table 3.8. *Proposed T8 Led Tube Fixture Characteristics*

T8 LED Tube Fixture	
Power (W)	21.5
Lumen Output (lm)	3,700
Lifetime (hrs)	70,000
Energy Label	A++

In order to evaluate the performance of the lighting retrofit in four different climatic regions, the existing T5 lighting fixtures were replaced with T8 LED tube fixture in Design Builder energy model. The lumen value of the T8 LED tube is 3700 lm, while the lifetime of this illumination is 70000hrs. Furthermore, the power of this lighting device is 21.5 W. Although it consumes less energy than the existing lighting (Existing lighting fixture power 36 W; lumen output 2500 lm), the amount of luminous flux of proposed lighting fixture is higher. (Table 3.8.)

In addition, the normalized power density value required for Design builder software to perform energy analysis was calculated. In this calculation, the power of T8 lamps (36 W), the number of lighting fixture (8), areas of the classes (46 m^2), and the luminous flux required in these classes (300 lux) were taken into consideration and normalized power density calculated as 1.2400 W / m^2-100 lux. After the calculation, this data was transferred to the Design Builder energy model. (Figure 3.15)

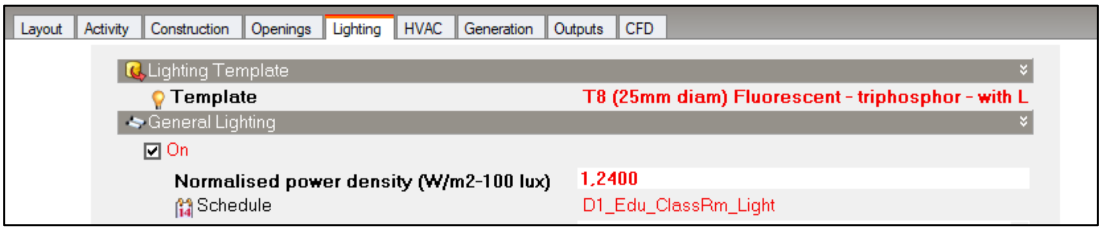


Figure 3.15. Proposed model lighting data

After preparing the energy models of four schools where lighting retrofit is proposed, energy analysis was performed with the help of Energy Plus energy simulation engine. The results obtained are presented in the Table 3.9 with the amount of existing school building energy consumptions.

According to this information, it is observed that the amount of lighting energy consumption and energy saving in the four climate regions are close to each other. At the same time, these data were directly related to the average sunshine duration of climate regions that is specified in Table 3.18.

According to the meteorological data, the average sunshine duration is in Climate Region I, followed by III, IV and II. Climatic Regions, respectively. (Table 3.18.) For this reason, energy saving is the highest in Climate Region II, which has the highest energy consumption. This region is followed by Climate Region IV, Climate Region III and Climate Region I, respectively. (Table 3.9.)

Table 3.9. *The energy consumption of lighting retrofit energy models in different climate regions*

Climate Regions	Energy Consumption (kWh)		
	Existing	Proposed	Saving
1.Region-Aydın	13,600	8,172	5,428
2.Region-Tekirdağ	14,211	8,443	5,768
3.Region-Ankara	13,680	8,176	5,504
4.Region-Erzincan	13,760	8,176	5,584

In addition, according to the price information obtained from the manufacturer companies for the T8 LED Tube lamps, which have been used in a total of 228 fixtures in the school buildings, the minimum cost of this lighting is 13TL, the maximum cost is 51TL and the most likely value is 37TL. In line with these prices, Total cost information is also given in the Table 3.10 and according to table the total cost varies between 2,964 TL and 11,628 TL. (Table 3.10.)

Table 3.10. *Lighting retrofit cost*

Retrofit 2- Lighting Retrofit Cost (TL)	
Minimum Cost	2,964
Most Likely Cost	8,436
Maximum Cost	11,628

Retrofit Type 3: PV Panel Installation

The use of renewable energy sources is vital for sustainability. In the existing school building, the amount of electrical energy consumption is very small compared to the amount of natural gas consumption (Figure 3.13.). However, meeting this energy with solar energy is not only important in terms of environmental, economic aspects, but also important in terms of social aspects. Since, using solar energy creates and increase the awareness about sustainability.

In addition, the performance values of the PV panels producing electricity by using solar energy expected to be various in different climate regions. Therefore, utilizing PV panels is proposed to evaluate the sustainability of it for the type school projects in different climate regions. The selected PV panels and their technical features are shown in Table 3.11.

Table 3.11. *Proposed PV panel technical specification*

Mechanical Characteristics	
Solar Cell	Polycrystalline 156mmx156mm square, 6x12 pieces in series
Dimension	Length: 1956 mm
	Width: 992 mm
	Height: 45 mm
Electrical Typical Values	
Rated Power	330 W
Rated Current	8.65 A
Rated Voltage	37.0 V
Short Circuit Current	8.95 A
Open Circuit Voltage	46.4 V
Module Efficiency	16.49%
Temperature Characteristics	
NOCT	45°C ± 2°C
Voltage Temperature Coefficient	-0.31 % / k
Current Temperature Coefficient	+0.06 % / k
Power Temperature Coefficient	-0.40 % / k

In order to evaluate the performance of the PV panel installation in different climate regions, roof type solar panels were adapted to the energy models of the existing school buildings in four climate regions.

In this research, in total, 15 PV panels with 320W electric power capacity were proposed for the type school building in each climate regions. These panels are placed on top of the roof of the building with 35° angle recommended for the city of Ankara. (Koçer, Şevik, & Güngör, 2016) (Figure 3.16.)

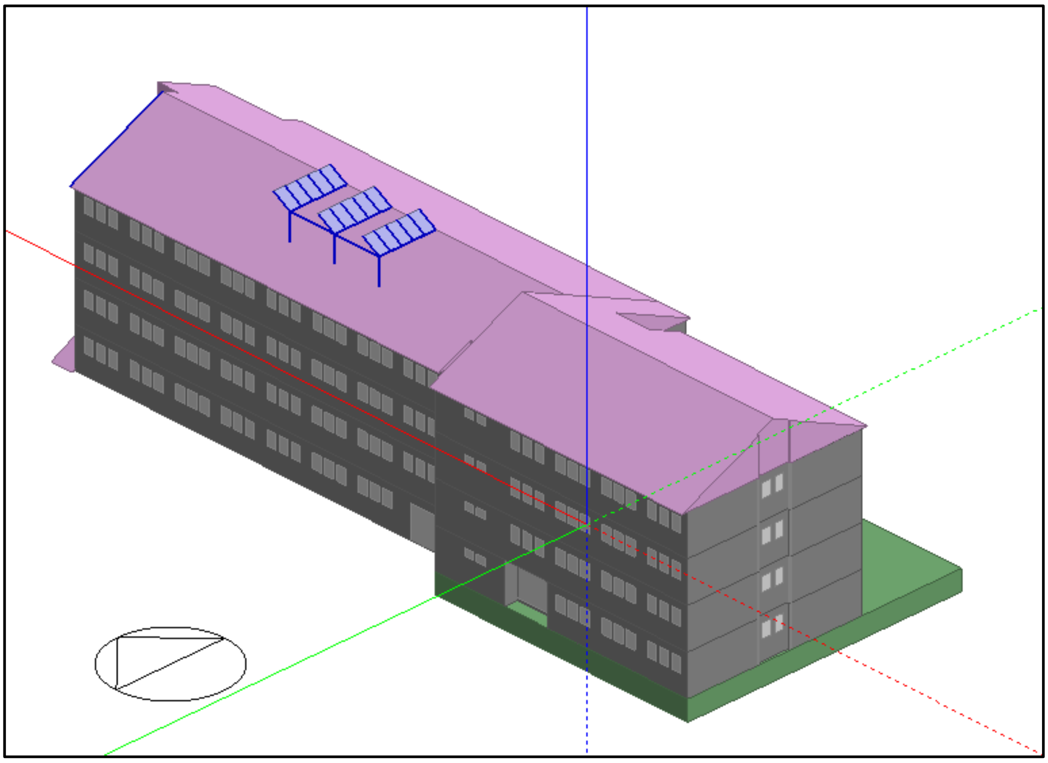


Figure 3.16. PV panel installation on the roof of school building

In the energy generation section of the Design Builder software, which allows the modeling of specific types of PV panels, proposed PV panel technical specification that is given in Table 3.11. are assigned. (Figure 3.17.) At the same time, temperature coefficient of open circuit voltage value which is not in the Table 3.4 is equal to the ratio of open circuit voltage to voltage temperature coefficient. Therefore, this value was also calculated. In the calculation, open circuit voltage value is 46.4V and voltage temperature coefficient value is 0.31% k. As s result, the temperature coefficient of open circuit voltage was calculated as 0.144 V / K and this value is also assigned to the energy model data. (Figure 3.17)

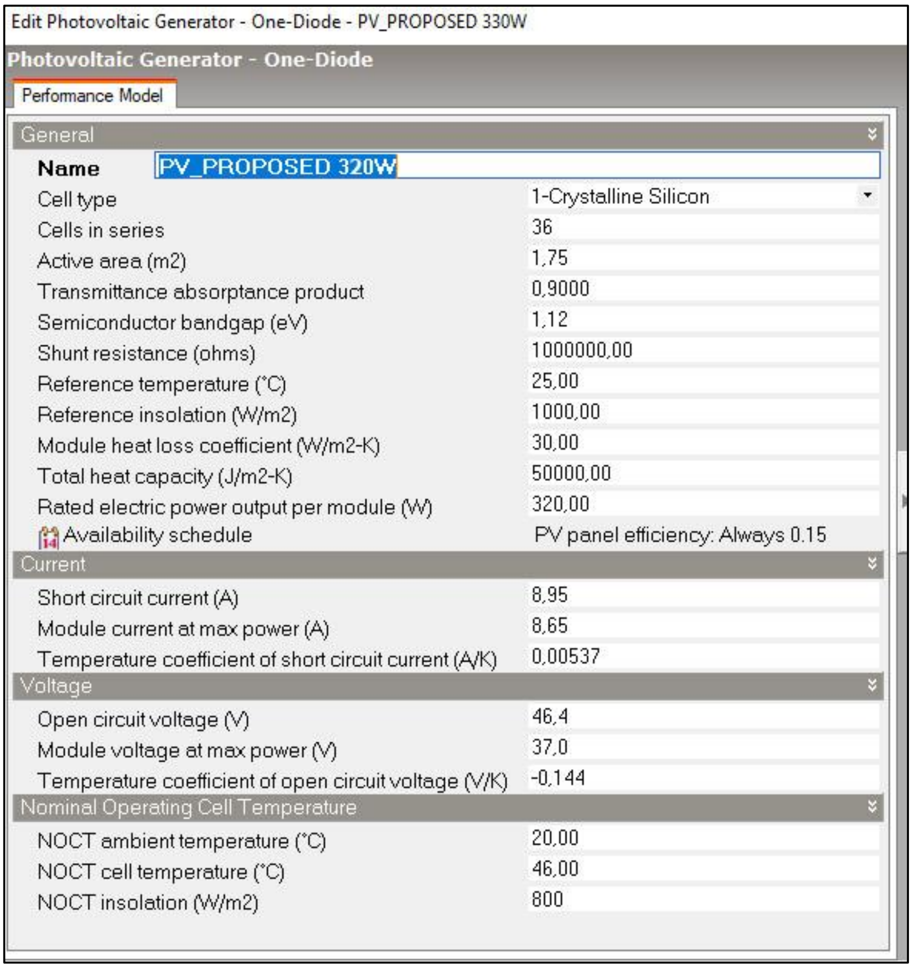


Figure 3.17. Design Builder model energy generation data of PV panels

After completion of PV panel model, the energy models prepared in the design builder program was simulated by Energy Plus simulation engine and the amount of energy generated by PV panels are given in the Table 3.12 below.

It has been observed that these values change in direct proportion to the average sunshine duration of climate types. (Table 3.18.) The lowest energy production is in the Climate Region II with the least average sunshine duration, while the highest energy production is in Climate Region I. (Table 3.12.)

Table 3.12. *The energy consumption of lighting retrofit energy models in different climate regions*

Climate Regions	Existing Energy Consmption (kWh)	Energy Generation (kWh)
1.Region-Aydın	13,600	8,866
2.Region-Tekirdağ	14,211	6,449
3.Region-Ankara	13,680	7,163
4.Region-Erzincan	13,760	6,900

The price information obtained from the manufacturers for the system which includes 15 PV panels with 330W power capacity and an inverter with a capacity of 5 kW, is shown in the Table 3.13 below. According to table, the minimum, most likely and maximum cost information of this system is 12,250 TL, 19,750 TL and 22,525 TL respectively. (Table 3.13.)

Table 3.13. *PV panels and installation cost*

Retrofit 3- PV Panel Installation Cost (TL)	
Minimum Cost	12,250
Most Likely Cost	19,750
Maximum Cost	22,525

Retrofit Type 4: Heat Recovery Unit Implementation

Another factor that increases the heating energy consumption of school building is the amount of heat lost during natural ventilation. In the natural ventilation process, some of the produced heat energy inside indoor air is thrown out of the windows in the body of the polluted air. The previously mentioned HRV devices are technologies that minimize the heating energy loss caused by natural ventilation (Ribe *et al*., 2019) (Al-Zubaydi & Hong, 2018) (Kassai, 2017).

In type 735 school buildings and many other school buildings, ventilation is provided by natural ventilation. At the same time, indoor air quality has a huge impact on not only occupant’s health but also on learning performance of the students. In other words, as mentioned before in the literature review section, indoor air quality has a significant impacts on student health, productivity and comfort in school building, and restriction of natural ventilation due to heat loss in school buildings will have a negative impact on health, comfort and productivity of the children (Şahin & Dostoğlu, 2015) (Kocabaş & Bademcioğlu, 2016).

Therefore, it is suggested to utilize decentralized/independent HRV devices which provide continuity of ventilation with minimizing heat loss and the evaluation of this retrofit type is exemplary for all other naturally ventilated schools. With these devices, it is aimed to increase the indoor air quality by providing continuity of ventilation in school buildings where there is no mechanical ventilation. The basic operating principle and energy recovery principles of these devices was mentioned in the literature review part. (Figure 3.19.)

In this project, the proposed HRV device has 2 connections in total, namely inlet and outlet. While the fan inside these devices blows the air inside for 70 seconds, it runs in reverse direction and blows the outside air inside. During the blowing of the heated and dirty air inside, the heat energy inside the air is transferred to the air to air heat exchanger of the device and the dirty air which has lost a significant part of its energy is discharged. In the other 70 second period, the heat energy stored in the air to air heat exchanger is transferred to the fresh and cold air taken from outside. Thus, the cold and fresh air taken from outside is heated before being fed to the interior space. Consequently, as a principle of energy recovery, energy in a system can be transferred to another system and this minimizes the heating energy load. (Figure 3.18.)

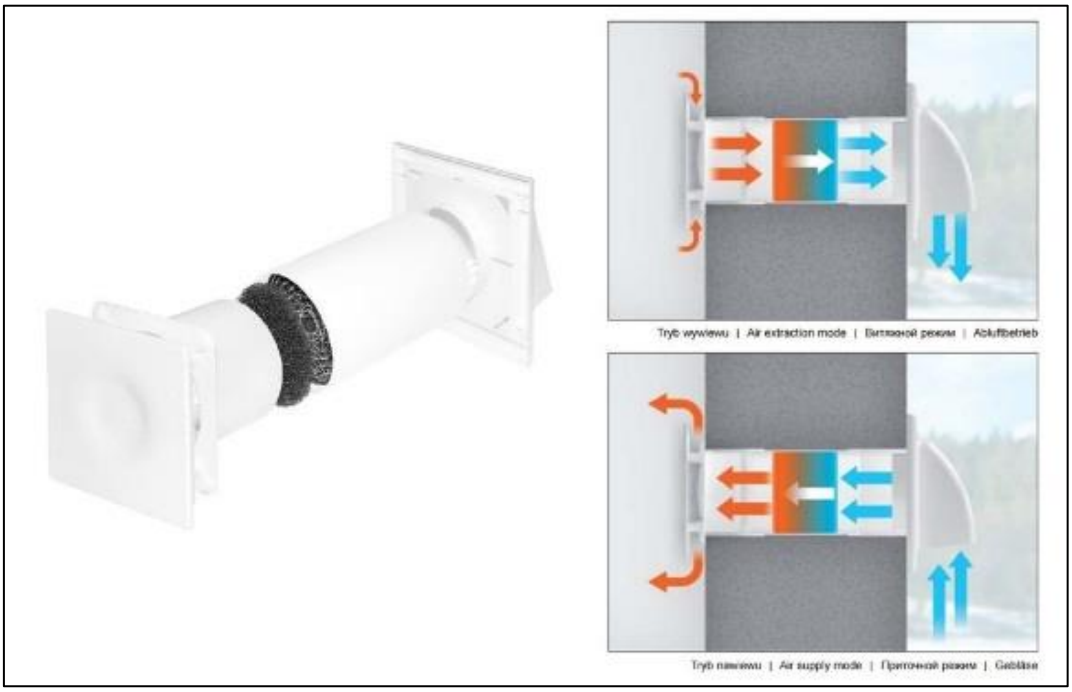


Figure 3.18. Proposed sample of decentralized HRV units (Source: "https://www.dampprevention.ie/en/vrt. Accessed: 10/05/2019.)

In accordance with the information received from the companies that manufacture, sell and install HRV devices, independent heat recovery devices shown in Figure 3.18. are proposed for the school buildings. At the same time, expert opinions and methods were used in the selection of the required HRV device and calculation of the number of devices required. These experts recommend 6 independent HRV devices for classes with 3.40m story height and 46 m^2 in existing school buildings. At the same time, this recommendation was confirmed by minimum ventilation rates according to ASHRAE standards. As shown in the Table 3.14. below, the minimum ventilation rate of the classes is 5 L/s.person. This value is equal to 9 m^3 fresh air per person per hour. At the same time, since the recommended HRV devices circulate 45 m^3 of air per hour, it is confirmed that one device should be proposed for every five people. According to this information, 6 HRV devices are recommended for each 30-person standard classes. As a result of these calculations, considering the total number of classes and sizes, it was found appropriate to propose 154 HRV devices to the type school structure.

Table 3.14. *Minimum ventilation rates in breathing zone (ASHRAE, 2015)*

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3	H	65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3	H	150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1
Media center	10	5	0.12	0.6	A	25	15	7.4	1
Music/theater/dance	10	5	0.06	0.3	H	35	12	5.9	1
Multiuse assembly	7.5	3.8	0.06	0.3	H	100	8	4.1	1
Food and Beverage Service									
Restaurant dining rooms	7.5	3.8	0.18	0.9		70	10	5.1	2
Cafeteria/fast-food dining	7.5	3.8	0.18	0.9		100	9	4.7	2
Bars, cocktail lounges	7.5	3.8	0.18	0.9		100	9	4.7	2
Kitchen (cooking)	7.5	3.8	0.12	0.6		20	14	7.0	2
General									
Break rooms	5	2.5	0.06	0.3	H	25	7	3.5	1

In addition, one of these devices consumes 3 W/h energy. This value is neglected in the energy calculations since the electricity consumption of this device is very low compared to the total electricity consumption.

Design builder energy model, which was prepared according to the capacity calculations and performance values, was analyzed with Energy Plus simulation engine. The energy saving amounts obtained as a result of the analyzes are as in the Table 3.15. According to the energy analysis, the energy saving amount is the most in Climate Region IV where the heating energy load is high, while the energy saving amount is the least in Climate Region I where the heating energy load is the least. (Table 3.15.)

Table 3.15. *The energy consumption of HRV unit implemented energy models in different climate regions*

Climate Regions	Energy Consumption (kWh)		
	Existing	Proposed	Saving
1.Region-Aydın	60,885	51,396	9,489
2.Region-Tekirdağ	107,027	86,550	20,477
3.Region-Ankara	191,937	162,809	29,128
4.Region-Erzincan	214,585	180,541	34,044

At the same time, according to the price information obtained from the manufacturer companies, the device and installation value of one of these devices ranged between 450 Euro and 650 Euro and the most likely value was 500 Euro. Based on these prices, the minimum, maximum and most probably cost values of this retrofit type are calculated and given in the Table 3.16. HRV unit implementation cost ranges from 487,179TL to 703,703TL. In this calculation, the value of 1 Euro was calculated as 7.03 TL. When these values are compared with other retrofit types, the initial investment cost of HRV devices is very high.

Table 3.16. *HRV units and installation cost*

Retrofit 4- HRV Unit Implementation Cost (TL)	
Minimum Cost	487,179
Most Likely Cost	541,310
Maximum Cost	703,703

Consequently, it was decided to evaluate four different retrofits about building envelope, mechanical system, electrical system and renewable energy sources in this study and these retrofit types are summarized in Table 3.17.

Table 3.17. *Proposed retrofit types*

Type	Retrofit Measures	Energy-Related Activities
Retrofit 1	Building Envelope	Insulate Walls
		Insulate Attic Space
Retrofit 2	Electrical System	Replace existing lighting with energy efficient LED lightings
Retrofit 3	Renewable Energy Sources	PV Installation
Retrofit 4	Mechanical System	Heat Recovery Units Installation

3.2.3. Characteristics of Climate Regions in Turkey

In Turkey, there are four climate regions according to TSE report (Turkish Standards Institute, 2009). The schools in the research are exemplified from these climate regions. However, these climate types do not directly correspond to the climate zones in international standards.

Design Builder program that is preferred for energy modeling offers an energy analysis based on ASHRAE climate types. For this reason, ASHRAE climate zones, which were defined according to the selected cities, were evaluated.

According to the Design Builder program, Ankara and Erzincan are in the 5A and 4B climate regions, respectively. However, according to the data published by the General Directorate of Meteorology, the annual temperature values of Erzurum are lower than Ankara and Erzurum have a cooler climate (General Directorate of Meteorology, 2019).

Due to this problem, the literature about this subject was examined and it was seen that Ankara was in the 4th climate zone according to ASHRAE standard (Ab, 2007).

Moreover, in the research of Öztürk *et al.*, Turkey's climate zones have been studied according to the Köppen-Geiger climate types (Figure 3.19.) (Öztürk *et al.*, 2017).

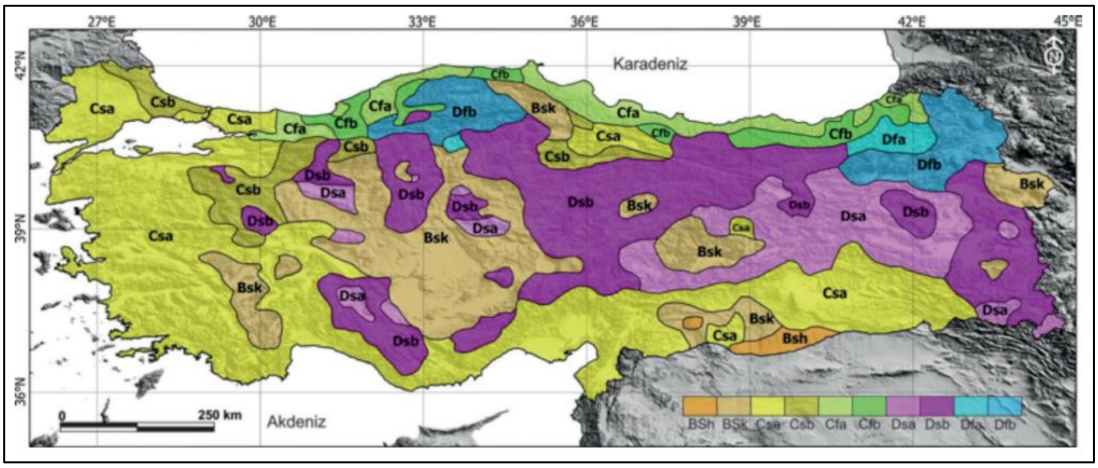


Figure 3.19. Köppen-Geiger Climate Zone in Turkey (Öztürk *et al.*, 2017)

When, the climate zone map determined by TSE superposed with this map, the new climate map is generated in Figure 3.20.

According to the Köppen-Geiger Climate Zone, selected climate zones Csa, Cfa, Bsk and Dsb correspond to the TSE climate regions I, II, III and IV respectively (Figure 3.9.).

Based on this information, ASHRAE climate types corresponding to Köppen-Geiger climate zones were determined and 3A, 3C, 4B and 5A climate types are determined for the climate regions I, II, III and IV, respectively (Table 3.18.).

As a result, Table 3.18., which includes the heating and cooling degree days, altitude, latitude and longitude values of the provinces by using the information obtained from the General Directorate of Meteorology, was formed. In this research study, it was emphasized that the values of the simulation model and the values in the above prepared table are consistent and parallel during the energy modelling and analysis process.

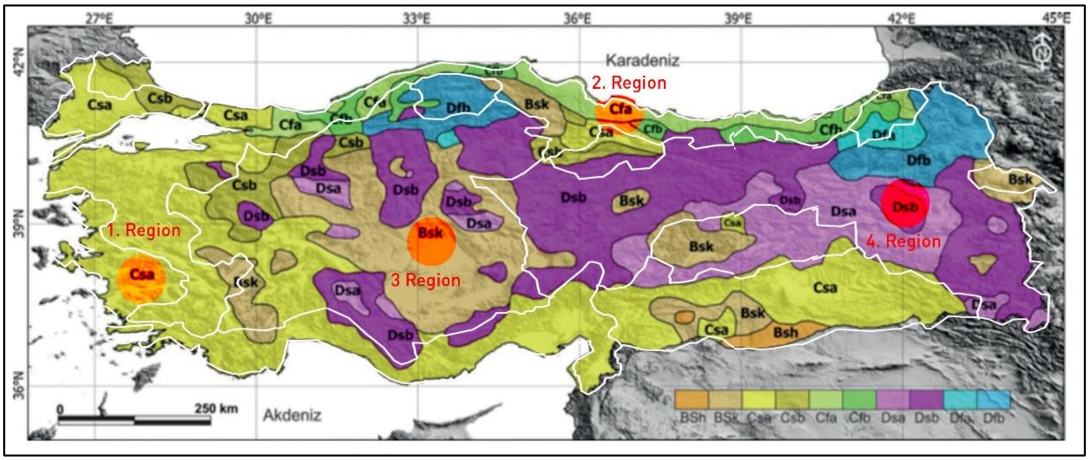


Figure 3.20. Superposition of TSE climate Zone and Köpper-Geiger Climate Zone Map

Table 3.18. *Climate Regions Characteristics*

TSE Climate Region	ASHRAE Climate Zones	Köppen-Geiger Climate Classification	City	Altitude (m)	Longitude	Latitude	HDD (T≤15 °C)	CDD (T>22 °C)	Average Sunshine Duration (h)(Annual)
1. Region	3A	Csa	Aydın	70	27:51 E	37:51 N	918	704	86
2. Region	3C	Cfa	Tekirdağ	3	27:31 E	40:59 N	1582	273	69
3. Region	4B	Bsk	Ankara	870	32:52 E	39:56 N	1951	211	82
4. Region	5A	Dsb	Erzincan	1214	39:29 E	39:44 N	2166	155	79

3.3. Research Approach - Sustainability Assessment of Retrofit Measures

Energy retrofit strategies are very important in terms of energy efficiency and sustainability. However, these strategies have different effects on energy efficiency and sustainability due to climatic differences in type projects.

In this research, the analysis of the sustainability of the energy retrofit strategies for the type 735 structure, which is a case study project, in different climates, and the retrofit studies were evaluated with a climate-based approach. Therefore, in 'Sustainability Assessment Model' section, it is explained how case studies are designed to evaluate the effect of different retrofit types on sustainability in different climates.

In the research of Jafari and Valentin (Jafari & Valentin, 2017) about assessing the sustainability impact of proposed energy retrofit, sustainability was defined as the sum of economic, environmental and social sustainability.

However, these three sustainability criteria should not be considered equally important for each project and the weight of these three criteria can be different for different cases. For some projects, while social sustainability is considered more important, economic sustainability may be prominent for some. In this research study, it is assumed that three sustainability criteria - economic, environmental and social - are equally important. In addition, the other scenarios-economic, environmental and social scenarios were also evaluated.

In this study, sustainability impact assessment methods are used in the research study of Jafari and Valentin (2017) and these methods are explained in detail in 'Sustainability Assessment Methods' section. In addition, it is aimed to investigate the relationship between the sustainability of retrofit types and climate types with the proposed case studies. In these examinations, while the impact of the proposed retrofit measures on the ecological and economic sustainability were reached by using the energy simulations and cost analysis, the impact on the social sustainability was reached through a survey conducted on educators.

3.3.1. Sustainability Assessment Model

In this section, in accordance with the purpose of this study, cases are described. Production of these cases with different types of climate and retrofit types is shown in the following diagram (Figure 3.21.) and this process explained with three steps.

After the explanation of case study process, the methods to be used in the evaluation of economic, ecological and social sustainability impact factors are presented in four sub-headings: economic sustainability assessment, environmental sustainability assessment, social sustainability assessment, sustainability assessment.

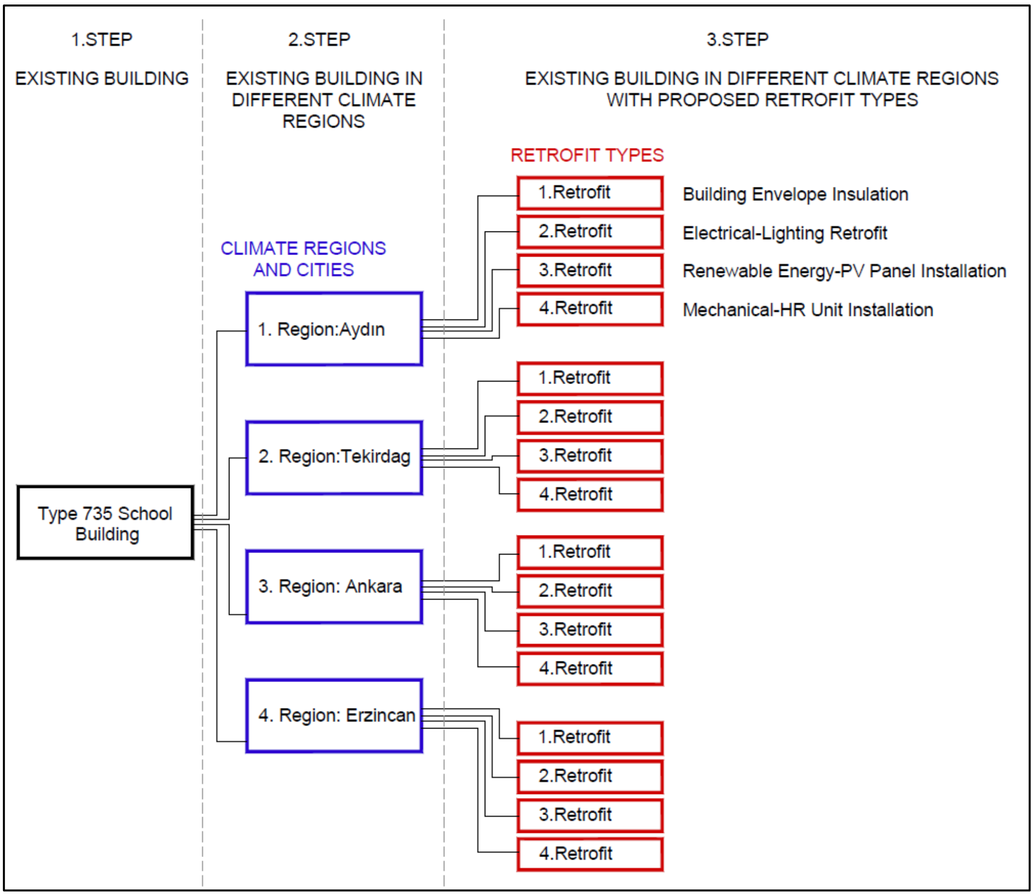


Figure 3.21. Diagram of analysis cases

Step 1

In this research study, according to the information obtained from the site visit the Ayrancı Anatolian High School building in Ankara, which is known to be the prototype 735 school project is modelled by using Design Builder software.

In design period, energy modelling is very important for the defining energy consumption of the building. There are various parameters that effect the energy simulation results such as material types, energy sources, environmental factors, regional parameters *etc*. However, for optimum realization of the energy simulations, energy model of the building should be simplified. Otherwise, simulation time that is required for the analysis is extended. In addition, the performance of the technical equipment to be used for this analysis may not be enough and the performance of these may need to be improved. In this respect, zoning strategy can be adapted for simplifying of the energy model. Zoning is an alternative to defining volumes of the model. Since, building is composed of many volumes that have various micro climatic conditions because of the sizes, functions, HVAC system characteristics, lighting, occupants, orientations and material characteristics (Bayraktar *et al.*, 2013).

Transferring the microclimatic data of each volume that forms the energy to the model may not be reasonable due to the simulation time and technical equipment performance. In addition, At the same time, some software allows only energy analysis of structures with a certain number of zones. For these reasons, the zoning strategy, which divides the building into regions by categorizing volumes with similar characteristics, enables to faster and easier results. In the research of Bayraktar *et al.* (2013), energy models made with different zoning strategies were subjected to analysis (Figure 3.22.). According to the results of this analysis, it is stated that the differences in the total amount of energy consumption of the energy models are negligible (Bayraktar *et al*., 2013).

As a result, in this research adjacent units that have same function were combined and modeled as a single zone (Figure 3.23.). By reducing the number of zones, the time required for energy simulation is reduced to the optimum level.

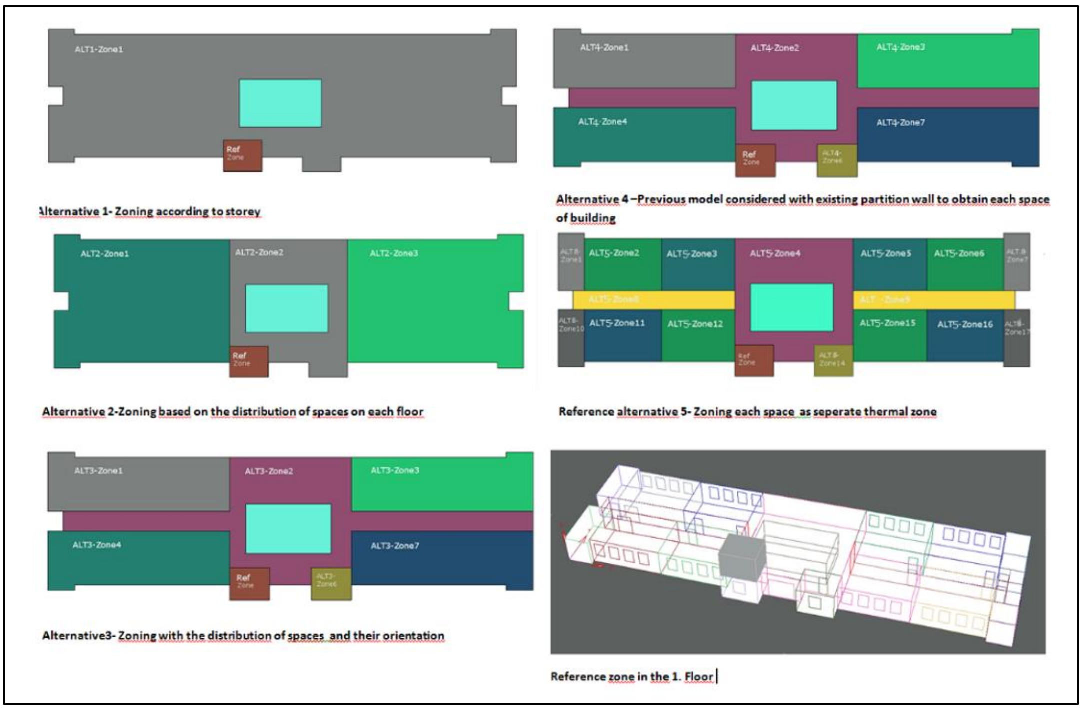


Figure 3.22. Alternative zoning strategies (Bayraktar *et al.*, 2013)

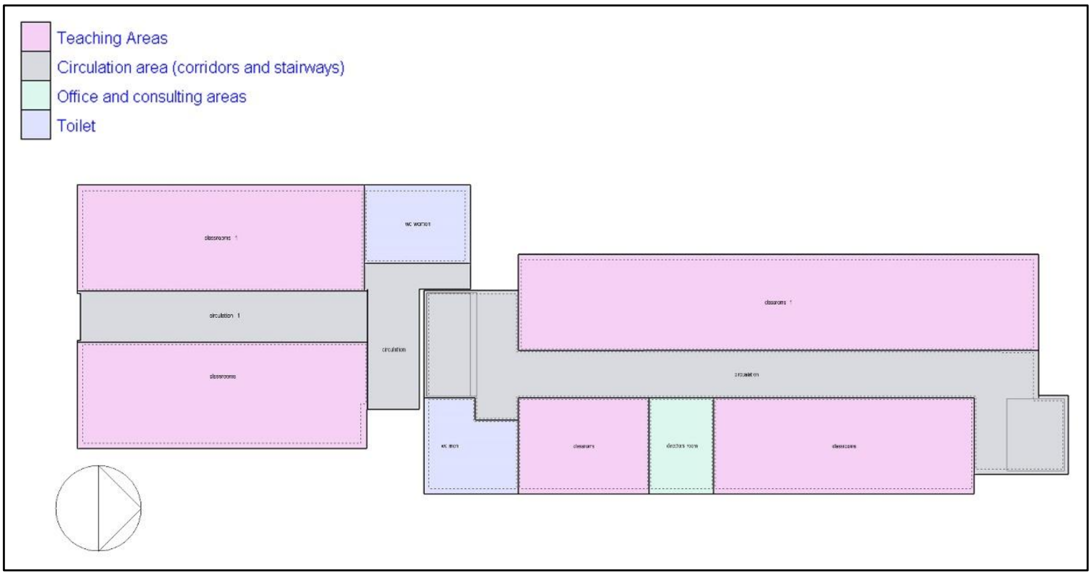


Figure 3.23. Zoning strategy at typical floor plan of school building

Step 2

In this research, energy model of the cases in the four climatic regions of the prototype 735 school project was prepared to reveal the relationship between climate and energy retrofit studies. However, due to the orientations of these school buildings in four climate regions are different, the actual orientations of the school buildings were neglected in this study and models were prepared assuming that the orientation of the schools in each region is the same as the Ayrancı Anatolian High School building in Ankara. (Figure 2.24.)

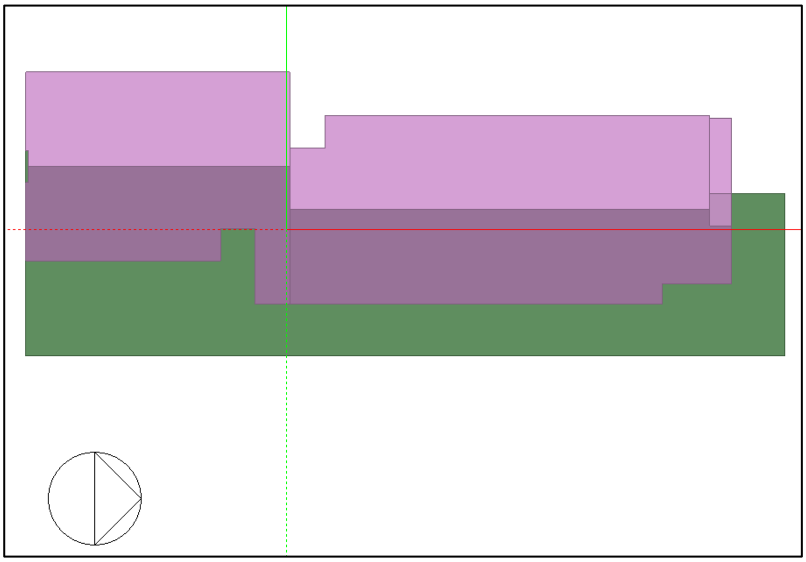


Figure 3.24. North-south orientation of Ankara Ayrancı Anatolian High School

However, before the assumption was made regarding the orientation subject, the following studies were done. After the modeling of the school building in Ankara (north-south orientation), energy model and energy analysis in different orientations such as east-west, northeast-southwest, northwest-southeast orientation of the building were performed. Because of these analyzes, there is no significant difference in energy load between the orientation alternatives. The biggest difference was found between east-west and north-south orientation. When the building in the North-South orientation is placed according to East-West orientation, the total energy load decreases by 2%. Therefore, to better analyze the relationship between climate and retrofit, orientation of the school projects in the other three climate regions was neglected.

Another assumption in the prepared energy model is the duration of artificial light usage. In the prepared energy model, the average illuminance of daylight is analyzed to define the duration of the use of artificial light for the current model. The average illuminance distribution because of daylight analysis for Aydın province which has the highest number of sunny days among 4 provinces is as shown in Figure 3.25. It is seen that the light distribution is not equal, and it is below the recommended value (300lux) in some places (Bruin-Hordijk & Groot, 2005). Based on this analysis, it has been assumed that artificial lighting is used in cases where daylight is insufficient in energy model. In other words, it is assumed that artificial lighting is used in cases where the illumination value of the point at the geometric center of the spaces falls below 300 lux.

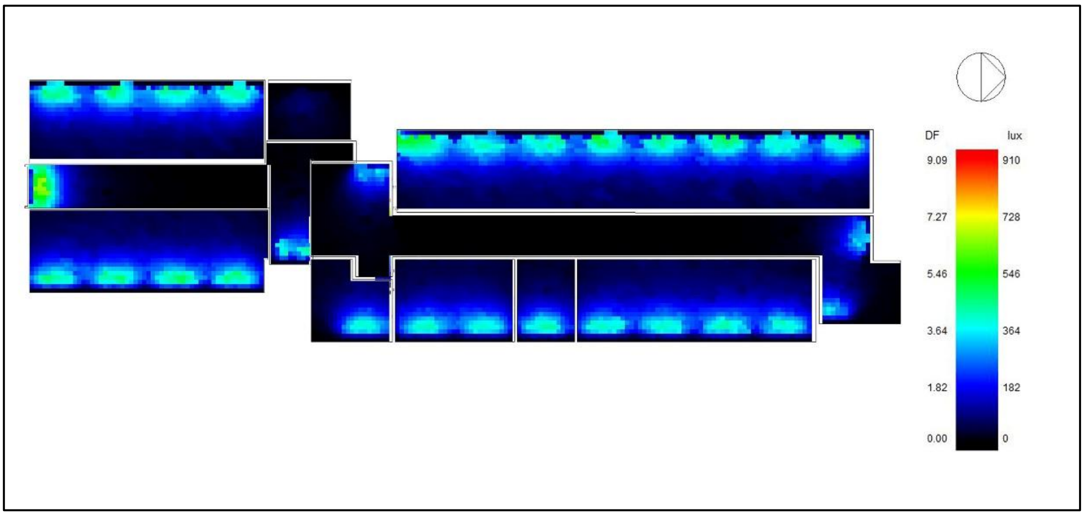


Figure 3.25. Daylight illuminance distribution of school building in Aydın

Step 3

After analyzing the existing school building in 4 climatic zones, another step is to implement the previously mentioned retrofit types to these building models. With these 16 different cases, it is possible to calculate the sustainability impact of different retrofit types implemented in different climate zones.

The economic, environmental and social sustainability assessment of each case should be carried out to evaluate the sustainability impact of proposed retrofit types. In other words, the sum of these values obtained as a result of these analyzes formed the sustainability impact (Figure 3.26.).

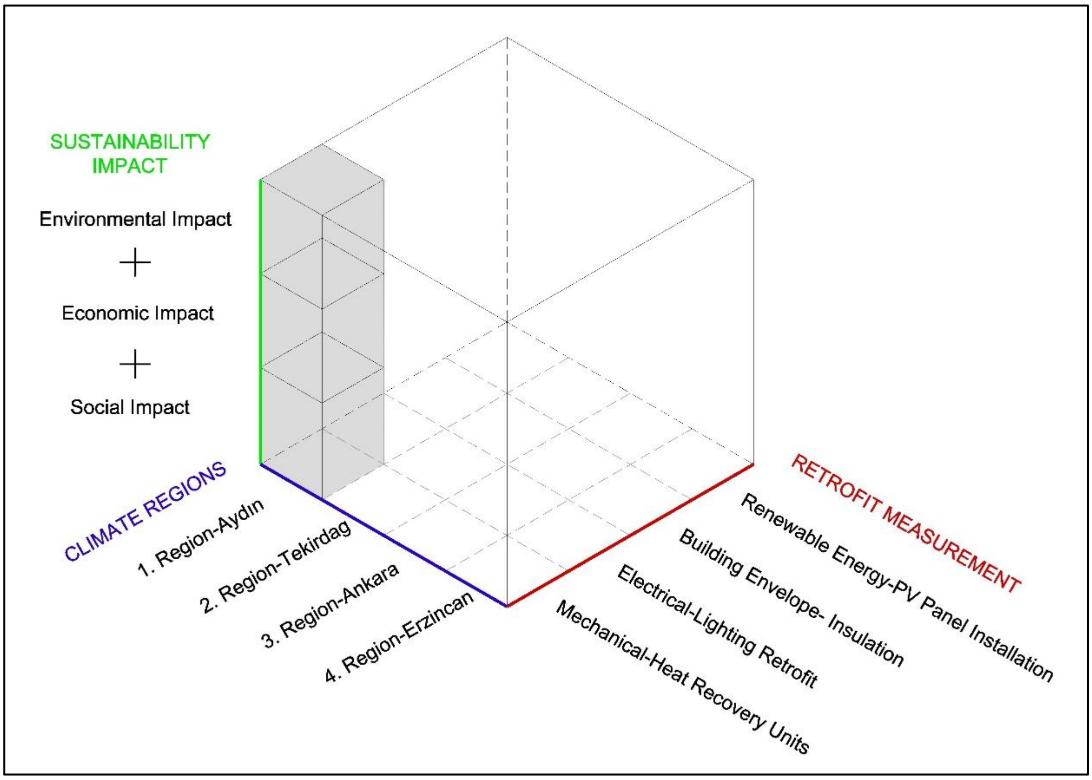


Figure 3.26. Sustainability impact assessment model

The analysis methods to be applied for these 16 cases are explained below under four sub-headings.

3.3.2. Sustainability Assessment Methods

Economic Sustainability Assessment

Economic sustainability can be evaluated by using different methods that was mentioned before (Vatalis *et al*., 2011) and payback period is one of the economic measurements for analyzing of investment. It can be defined as the time that is required for the recovery of the additional investment (Mahlia *et al.*, 2011).

In this study, payback period is enables to measure the economic sustainability impact of the retrofit measures. In their research paper, Jafari and Valentin states that payback period that is an indicator of economic impact is measure with the time value money (Equation 3) (Jafari & Valentin, 2017).

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d} \right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d \right) \tag{3}$$

In this formula, *n* represents the payback period, while initial investment cost of retrofit types and expected annual energy cost saving are defined as *IIC* and *AECS*. In addition, discount rate is described with *d*.

IIC is the sum of material, equipment and labor cost spent for retrofitting measure. *AECS* is the expected cost saving provided by these retrofitting measure in the amount of annual energy expenditure of the building (Jafari & Valentin, 2017).

In this study, *AECS* is evaluated by Energy Plus that is energy simulation tool offered by Design Builder software. While only the first investment cost and energy consumption cost are considered in the payback period calculation, other cost types such as maintenance cost, tax rebate and operational costs have been neglected. In addition, the cost estimation of *IIC* and *AECS* is made by using PERT distribution that is preferred for completion time and cost estimation. PERT distribution called the beta-PERT is a three-point estimation technique that uses minimum (optimistic), maximum (pessimistic) and most probable values of expected costs. By using this technique, PERT probability distribution of the AECS and IIC are established.

After estimation process, the probability distribution of retrofit measures in different climate regions is calculated by using RiskAMP software that is Monte Carlo Simulation engine for Microsoft Excel.

The calculated payback periods are an indicator of the economic sustainability of retrofit types and the retrofit type with a lower payback period is economically more sustainable. There is an inverse relationship between the economic sustainability impact and the payback periods of each retrofit types. Therefore, economic impacts (ECI) factor of each retrofit types are calculated by the following equation (Equation 4).

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \tag{4}$$

In this Equation 4, i^{th} represents the type of retrofitting measure and payback period of i^{th} defined as n_i. k is the total number of proposed energy retrofitting measures. For example, in this study k is equal to 4. According to this equation, *ECI* is a normalized value ranging from 0 to 1.

In the Figure 3.27, assessment of economic sustainability impact of 1. Retrofit Type that is proposed in Climate Region I is presented with a diagram. In this diagram, it is shown that average payback period is calculated by using the amount of annual energy cost saving and, minimum, maximum and most probable cost of Retrofit 1. According to different retrofit cost options, PERT probability distribution of payback period, is calculated by using Monte Carlo Simulation engine and average payback period value is obtained. In addition, it shown that the economic impact (ECI) of Retrofit 1 calculated by considering the payback periods of other retrofit (ECI) types in the same climate region. (Figure 3.27.)

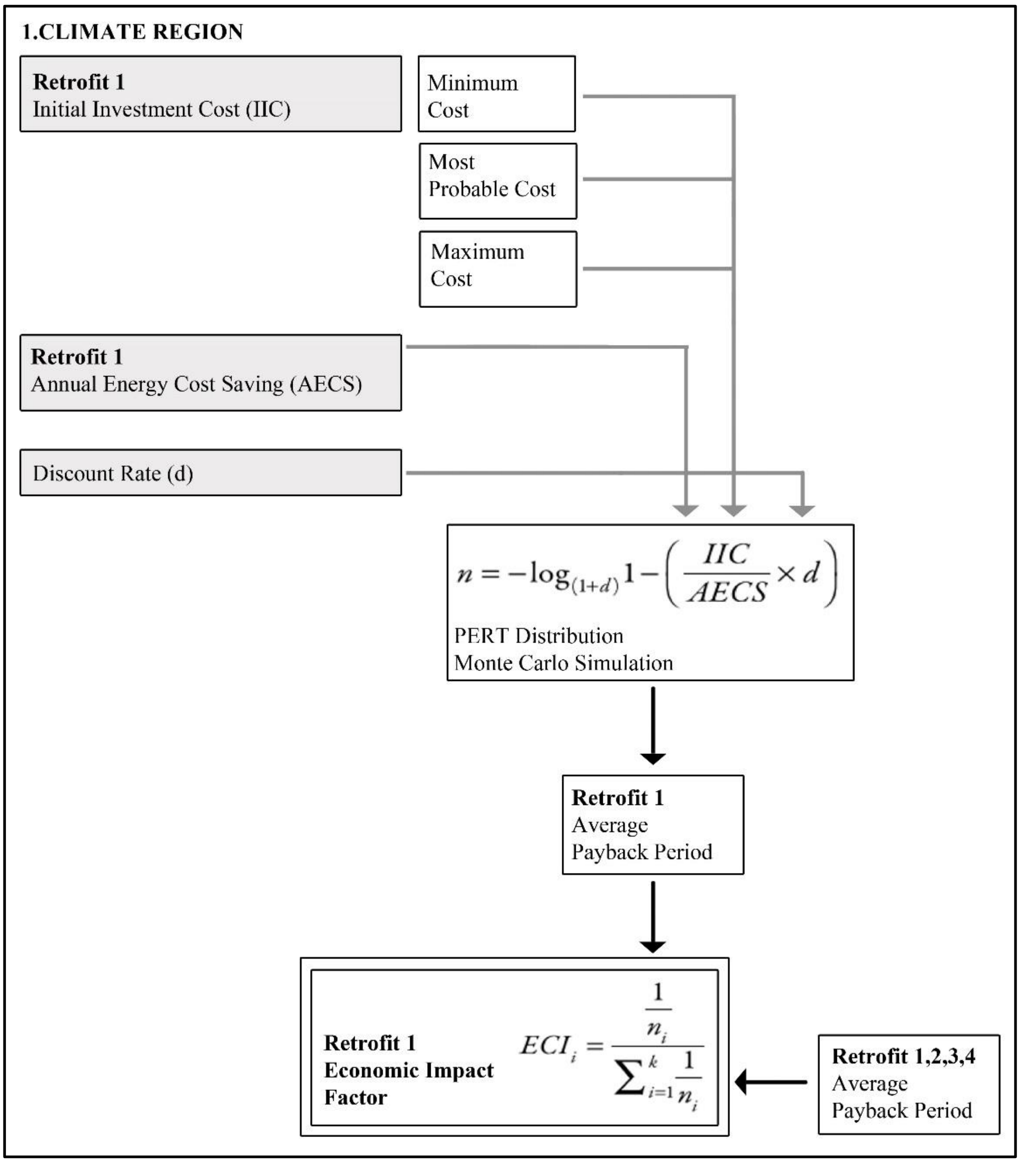


Figure 3.27. Diagram of economic sustainability assessment

For example, the economic sustainability calculation of envelope insulation for the school building in Ankara is shown in Figure 3.28. According to this figure, the payback period was calculated as 3.16 years and the economic impact factor was calculated as 0.41. In addition, calculations for different climate regions and different retrofit types are included in the Appendix F.

ANKARA

1.RETROFIT-ENVELOPE INSULATION	kWh	TL
Ankara Annual Energy Saving	66,313	35643.768

Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	75,505	35,644	2,461
most likely value	95,677	35,644	3.219
maximum value	110,806	35,644	3.823

PERT Distribuiton	90,007.81	35,643.77

Discount Rate	0.0915

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d} \right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d \right)$$

Payback Period Distribuiton Function(n)	3,000
Payback Period Average(n)	3.164

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}}$$

Economic Impact of A Retrofit(n)	0.414

Figure 3.28. Economic sustainability assessment of envelope insulation in Ankara

Environmental Sustainability Assessment

Providing energy efficiency in building enables to decrease impact of the building to the environment during life-cycle. Energy efficiency in building has many environmental benefits such as reduction of greenhouse gases emissions, preventing damages to the nature and decreasing pollutants loads (Jafari & Valentin, 2017).

There are various methods for assessing the environmental sustainability of measures. In this study, the amount of greenhouse gas emissions caused by electricity generation from the combustion of fossil fuels is an indicator for measuring the ecological impact of retrofitting measures. Therefore, power emissions factor depending on which sources are consumed, is also critical in terms of greenhouse gases emissions.

Jafari and Valentin (2017) are used the term of CO_2-equivalent reduction for defining greenhouse gases as a common unit to evaluate environmental impact of retrofit measures. They defined the term of CO_2-equivalent as the amount of CO_2-equivalent for CO_2, NO_x and SO_2 that is not generated because of the retrofit measures' energy saving. In their study, CO_2-equivalent reduction equation is presented as Equation 5 (Jafari & Valentin, 2017).

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2}\right) + \beta\left(AES \times E_{SO_2} + AGS \times G_{SO_2}\right) + \gamma\left(AES \times E_{NO_x} + AGS \times G_{NO_x}\right) \tag{5}$$

In this equation, *AES* and *AGS* are the expected annual energy saving in Kwh and the expected gas saving in MBtu respectively. *Ei* is the amount of air emission release to generated 1Kwh of electricity and *Gi* is the amount of the air emission releases to consume 1MBtu of natural gas. In addition, α, β, γ are the conversion factors for CO_2, SO_2 and NO_x.

However, the amount of CO_2 emissions caused by the consumption of different fuel types in Turkey are provided in TEİAŞ report (TEİAŞ General Directorate, 2019) and there is no information is available about the amount of other greenhouse gases emissions such as SO_2 and NO_x. Table 3.8. summarizes the air emission quantities caused by electricity and natural gas generation for Turkey. As a result, the CO_2-equivalent reduction equation is partially revised according to available information about energy emission factors (Equation 6). The conversion factor that is used for CO_2 (α) is equal to 1.

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2}\right) \tag{6}$$

Table 3.19. *Energy emission factors (TEIAŞ General Directorate, 2015)*

Fuel Type	GHG emission indicator (kg eq. CO_2/kWh)
Electricity	0.618
Natural Gas	0.819

The amount of saving energy as electricity and natural gas (*AES* and *AGS*) is calculated by energy simulation tool Energy Plus and Design Builder Software. After these calculations, the annual CO_2-Eq reduction is calculated by using Equation 6. The retrofit measure which saves more CO_2-Eq, is more preferred environmentally.

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i} \tag{7}$$

The equation that is given above (Equation 7) is used for calculation of the environmental impact of retrofit measures. ENI_i defines the environmental impact factor of i^{th} retrofit measure. Moreover, ENI_i is the normalized environmental impact factor ranging from 0 to 1.

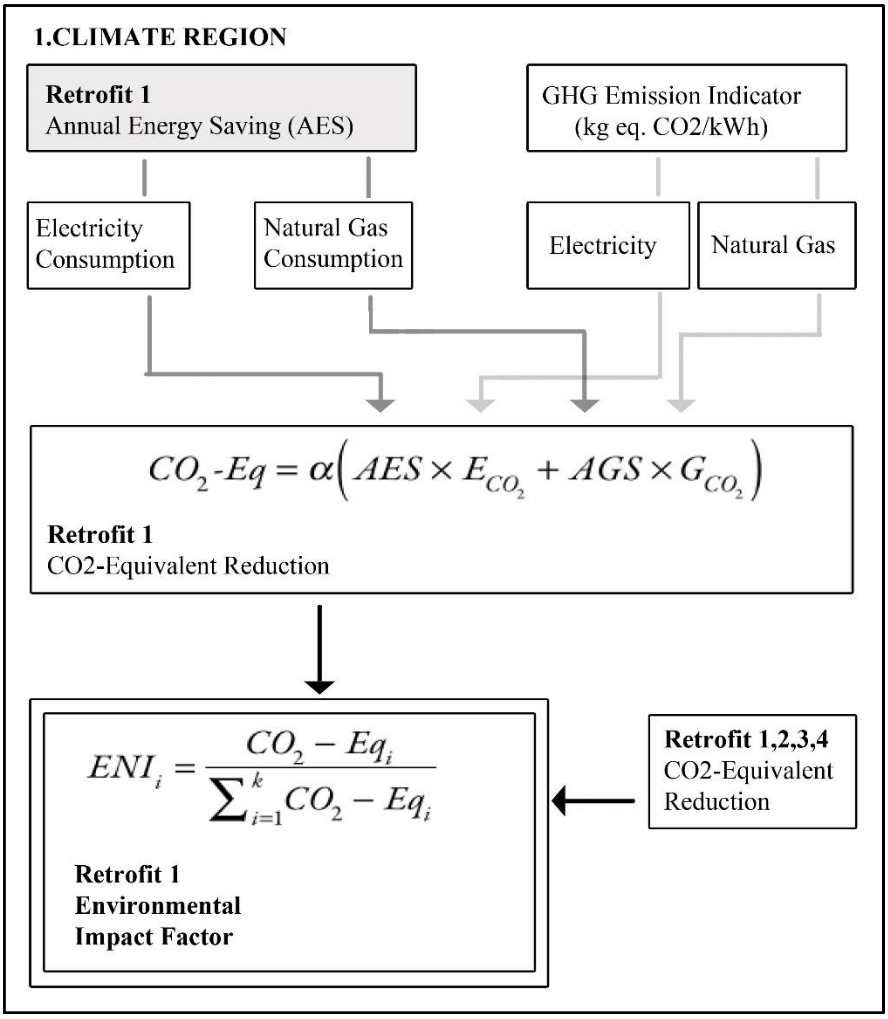


Figure 3.29. Diagram of environmental sustainability assessment

In the Figure 3.29, the evaluation of environmental sustainability impact of Retrofit 1 proposed in Climate Region I is explained with a diagram. As illustrated in this diagram, the environmental sustainability assessment is based on the amount of energy savings provided by Retrofit 1. Based on the current energy emission factor in Turkey, CO_2-equivalent reduction is calculated. After, the ratio of calculated CO_2-equivalent to the sum of the other CO_2-equivalent reduction values provided by other retrofit types in the same climate region is equal to the environmental impact factor (ENI) of Retrofit 1 in Climate Region I. (Figure 3.29.)

For example, the environmental sustainability calculation of the envelope insulation made for school building in Aydın are shown in the Figure 3.30. According to this figure, the amount of energy saving of envelope insulation is 19301 kWh in Aydın and according to calculated amount of CO_2-equivalent reduction, environmental impact was calculated as 0.486. (Figure 3.30) Moreover, calculations for different climate regions and different retrofit types are included in the Appendix F.

AYDIN		
Energy	Units	Expected Annual Energy Saving
		1.R-Envelope Insulation
Electricity	kWh	19,301

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2}\right)$$

CO2-Eq	**kg eşd. CO2/kWh**	**15,807.519**

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i}$$

ENI (Environmental Impact)	**0.486**

Figure 3.30. Environmental sustainability assessment of envelope insulation in Aydın

Social Sustainability Assessment

Evaluating the social sustainability is important for assessing the level of sustainability of the building. According to Jafari and Valentine (2018), social benefits can be categorized into three level: society level, community level and building level. In this study, to evaluate the social impact of the energy retrofit measures, it is concentrated on the occupants of the school building at the building level. According to characteristics of the school buildings, positive effect of the retrofitting measures is categorized into three main topics:

•Health: Development of indoor air quality have positive outcome on occupant's health (Jafari & Valentin, 2017) and students' health growth in school building (Bernardo *et al.,* 2017). To increase indoor air quality in school, ventilation and humidity rates should be considered (Saraiva *et al.,* 2018).

•Comfort: Indoor temperature, indoor air quality and lighting environment affects the occupants' comfort. To improve the indoor environment quality, it is necessary to provide thermal, visual and acoustic comfort (Saraiva *et al*., 2018).

•Productivity: Productivity of students and teachers is directly depended on the learning environment quality. Providing thermal comfort, developing indoor air quality, creating proper lighting environment and quiet atmosphere support learning facilities by increasing productivity (Bernardo *et al.,* 2017).

In this study, survey is decided as method for evaluating the impact of the proposed retrofitting measure on school building occupants. A questionnaire is proposed according to energy retrofit measures and their positive impacts. It has basically three parts: Introduction, Question 1 and Question 2 Group.

•Introduction: The participants are informed about the subject, purpose, number of questions and type of the questionnaire.

•Question 1: Participants are asked to decide the level of importance of social benefits (health, comfort and productivity) of energy retrofits. Question 1 is prepared as five points Likert scale: (5) very high importance, (4) high importance, (3) moderate importance, (2) low importance, (1) very low importance. With the answers of this questions, it is aimed to calculate the relative importance index of social benefits.

•Question 2 (group of questions): Participants are asked to decide the level of impact of each energy retrofit measures on defined social benefits (health, comfort and productivity)

This question group consists of four question that are also prepared as five points likert scale: (5) very high impact, (4) high impact, (3) moderate impact, (2) low impact, (1) very low impact.

In this study, relative importance index (RII) method that have been used to evaluate the relative importance of different factors in some researches (Heravi & Jarafi, 2014)

(Jafari & Valentin, 2017) is preferred to decide *RII* of defined social benefits of energy retrofitting measure (Equation 8).

$$RII = \frac{\sum W_1}{A \times N} \tag{8}$$

In Equation 8, *RII* defines the relative importance factor of social benefits and W_1 is each response that is given for the level of importance of each social benefit ranges from (1) to (5). *A* represents the highest weight of importance (which is five for this study) and *N* describes total number of survey respondents.

The Question 2 prepared to evaluate how different retrofit studies affect the defined social benefits is used in the Impact Factor calculation (Equation 9).

$$IF = \frac{\sum W_2}{A \times N} \tag{9}$$

In Equation 9, while *IF* represents the impact factor, level of impact that ranges from (1) to (5) is described with W_2.

After impact factor calculation, social impact of a retrofitting measure can be defined as Equation 10:

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

(10)

In this equation, while social impact index described with *SII* for a retrofitting measure, *i* is the social benefits of retrofitting measure. RII_i represents the relative importance index of the i^{th} social benefits and IF_i is the impact factor of the energy retrofitting measure i^{th} social benefits. *M* is the number of social benefits categories that is three for this study.

According to *SII* equation, the retrofitting measure that have higher *SII* is more preferred one in terms of social sustainability. For evaluating social impact of each retrofitting measure, social impact equation can be used (Equation 11).

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

(11)

In this equation, SO_i represent the social impact of i^{th} retrofitting measure and the social impact of index of the i^{th} energy retrofitting measure described as SII_i. As a result, SO_i is the normalized *SII* ranging from 0 to 1.

In addition, assessment of the social sustainability impact of Retrofit 1 is explained in Figure 3.31. In this diagram, firstly, the level of importance index of the social benefits provided by the retrofits in the school buildings is calculated with the responses of the participants to the first question of the survey. The ratio of the sum of the values of all answers to the total possible maximum weight is equal to the level of importance index (RII).

Secondly, the level of impacts of the retrofits is evaluated with the answers given to the 2., 3., 4. and 5. questions of the survey. The ratio of the total responses of the participants to the total possible highest weight gives the impact factor (IF) of the Retrofit 1 on health, comfort and productivity factors.

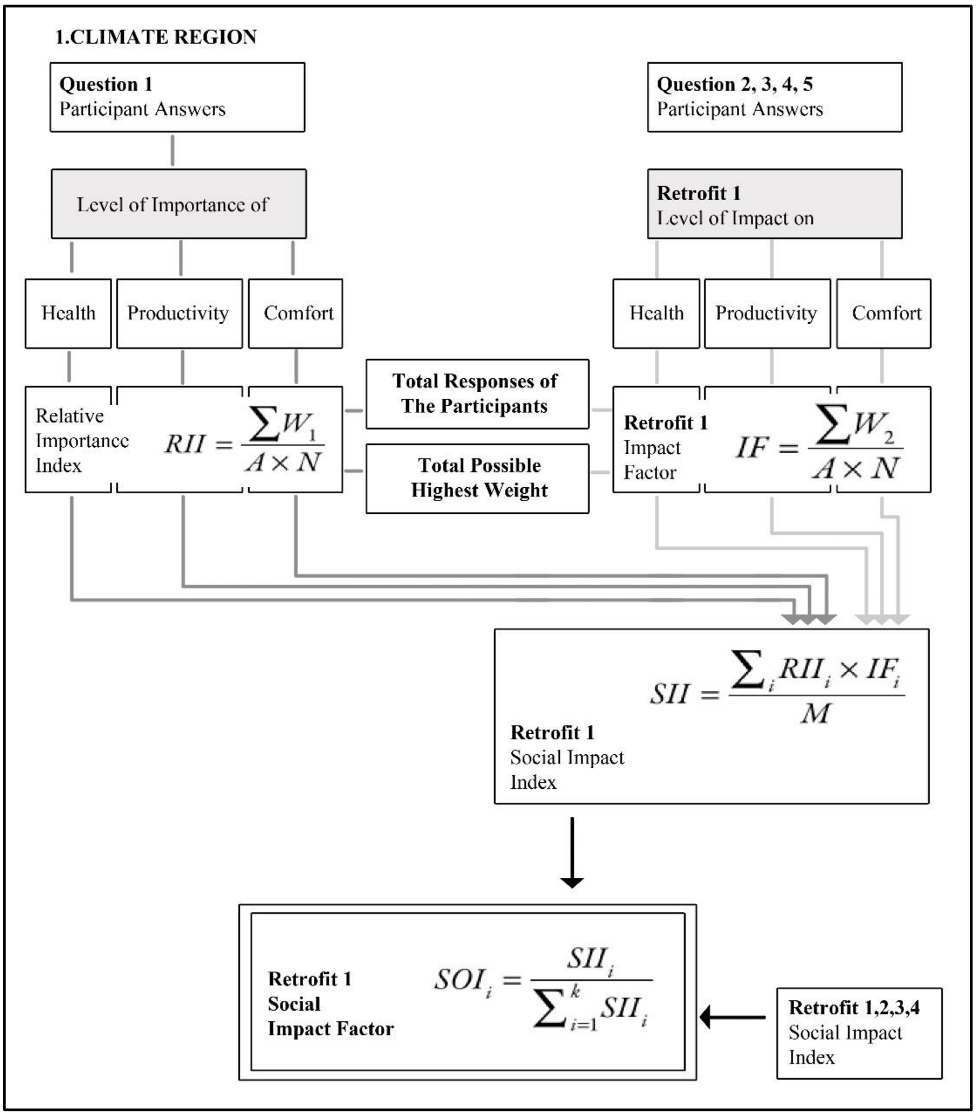


Figure 3.31. Diagram of social sustainability assessment

Finally, the ratio of the multiplication of the level of impacts of Retrofit 1 and the relative importance indexes (RII) to the number of social benefits categories (3) gave the social impact index (SII). The ratio of the social impact index to the sum of the social impact index found for all retrofit types in the same climate region is equal to social impact factor (SOI).

1.RETROFIT-ENVELOPE INSULATION

	LEVEL OF IMPORTANCE			LEVEL OF IMPACT		
PARTICIPANT	Health	Comfort	Productivity	Health	Comfort	Productivity
Sum of Responses	**154**	**132**	**152**	**137**	**134**	**135**
Total Possible Heighest Weight	**155**	**155**	**155**	**155**	**155**	**155**

$$RII = \frac{\sum W_1}{A \times N} \qquad IF = \frac{\sum W_2}{A \times N}$$

Relative Importance Index (RII)			Impact Factor (IF)		
0.994	**0.852**	**0.981**	**0.884**	**0.865**	**0.871**

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

Social Impact Index(SII)
0.823

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

Social Impact of Retrofit Type 1 (SOI)
0.256

Figure 3.32. Social sustainability assessment of envelope insulation

For example, the impact of envelope insulation on social sustainability is calculated in the Figure 3.32. According to this calculation, relative importance indexes of health, comfort and productivity factors were calculated. According to this calculation, the relative importance index of the health factor is the highest and this value is 0.994. In addition, the impact level of envelope insulation on these factors was calculated separately and according to this calculation, it has the most impact on health. As a result, the social impact of the envelope isolation was calculated by using the equations shown in the figure and it was calculated as 0.256. (Figure 3.32)

Sustainability Assessment

The sustainable impact of the proposed energy retrofitting measures is equal to sum of economic impact, environmental impact and social impact and it is also described with Equation 12 (Jafari & Valentin, 2017):

$$SUI_i = (a \times ECI_i) + (b \times ENI_i) + (c \times SOI_i) \tag{12}$$

In this equation, SU_i represents the sustainable impact of i^{th} retrofitting measure and ECI_i, ENI_i, SOI_i are economic, environmental and social impacts respectively. In addition, a, b and c are the importance weight factor of the impact categories. According to decision maker preferences, one of the scenarios can be selected from the Table 3.9. and by using these factors sustainable impact of energy retrofit scenarios can be evaluated and ranked. The energy retrofitting measure which have higher sustainable impact is more preferred in terms of sustainability. Jafari and Valentin discussed four different scenarios in their study and stated that these scenarios will calculate the sustainability according to different scenarios according to which criteria the projects attach importance to. (Table 3.9.)

Table 3.20. *Different importance weight factor for different scenario (Jafari & Valentine, 2017)*

Scenario	Importance Factor		
	a	b	c
Equal Importance to All Criteria	33%	33%	33%
Economic Scenario	80%	10%	10%
Environmental Scenario	10%	80%	10%
Social Scenario	10%	10%	80%

In this study, equal importance scenario that all the criteria are rated with equal importance (%33) is selected scenario for evaluation of sustainable impact. In addition, economic, ecological and social scenarios are scenarios where their own impact factors are higher than others. The effect factors were determined as 80% for the higher effect and 10% for others.

3.4. Parameters in the Process of Sustainability Impact Assessment

Sustainability is equal to the sum of economic, environmental and social sustainability as explained in the 'Data Analysis' section. Therefore, all parameters affecting these three factors directly affect the sustainability impact of retrofits. These can be summarized as follows: retrofit measures payback period (that is calculated by using initial investment cost and annual energy cost), CO_2 equivalent reduction (that is directly related with annual energy saving) and retrofits impact level on social benefits of sustainability (health, comfort and productivity)

In addition, climate characteristics of project location and existing school building energy load profile are the other factors affecting the sustainability impact assessment of proposed 16 case studies.

3.4.1. Climate Characteristics

TSE suggests 4 climatic regions in Turkey where the set has different climatic characteristics of each other: temperature, humidity, precipitation *etc*. (Turkish Standardization Institute, 2009)

It is also known that outdoor condition directly affects the indoor environment condition and the amount of energy consumed for providing comfort conditions in the interior environment varies for each climate regions (AlFaris *et al*., 2016). Therefore, heating and lighting energy loads of the existing school building in each climate regions are different (Figure 3.6.). In the literature, it is also stated that the performance of retrofit measure is affected by climate factor (Liu & Ren, 2018) (Aktemur & Atikol, 2017) (Yao *et al*., 2016) (Ashrafian *et al*., 2016).

Hypothesis I:

Null Hypothesis:

There is no relationship between economic sustainability impact of retrofit measures and climate characteristics.

Alternative Hypothesis:

Climates characteristics affects economic sustainability impact of retrofit measure.

Hypothesis II:

Null Hypothesis:

There is no relationship between environmental sustainability impact of retrofit measures and climate characteristics.

Alternative Hypothesis:

Climates characteristics affects environmental sustainability impact of retrofit measures.

3.4.2. School Buildings Energy Load Profile

According to the initial energy analysis, the energy load profile of the existing school buildings in each climate regions was mentioned in the 'Materials' section and shown in Figure 3.6. According to this analysis, the heating energy load is much more than the lighting energy load in school buildings. Therefore, school buildings have a specific energy load profile.

In addition, it is also known that each type of retrofit measure has an effect on different energy loads. For example, envelope insulation and heat recovery unit installation decrease the amount of energy consumed for heating; PV panel installation and lighting retrofit enables to reduces the need for electricity.

Hypothesis III:

Null Hypothesis:

There is no relationship between economic sustainability impact of retrofit measures and energy load profile of the school buildings.

Alternative Hypothesis:

Energy load profile of existing school buildings affects the economic sustainability impact of retrofits.

Hypothesis IV:

Null Hypothesis:

There is no relationship between environmental sustainability impact of retrofit measures and energy load profile of the school buildings.

Alternative Hypothesis:

Energy load profile of existing school buildings affects the environmental sustainability impact of retrofits.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of the analysis are obtained according to the methods mentioned in the material and method chapter. The results are presented with comparable tables and graphs. According to results, the parameters affecting these results are discussed.

4.1. Economic Impact

To calculate of payback period, initial investment cost and expected annual energy cost saving are the necessary cost categories.

In the initial investment cost calculation of implemented retrofit measure, the sources that were used are ‘General Price Analyzes of Construction Repot 2019’ and ‘2019 Construction and Installation Unit Prices Report’ (TR Ministry of Environment and Urbanisation, 2019); and cost estimator experts working in companies related to retrofitting measures. In addition, for the annual energy cost saving calculations, Energy Plus energy simulation engine available within the Design Builder Software. As a result, to implement the beta-PERT distribution method, 3 different costs (minimum, maximum and most probable costs) were obtained for the initial investment cost and energy saving cost by using these sources.

Another variable in the payback analysis account is the discount rate given in Equation 3. Discount rate is a continuously changing value depending on the economic situation of the countries. According to the CEIC data (CEIC, 2019), when we look at the discount rate of the last 5 years, we see that it is generally between 8% and 10%.

However, the discount rate in 2018 increased to 18,5% more than other years. For this reason, the average of the discount rate values between 2017 and 2012 is used in the Equation 3 of the payback analysis calculations and it is calculated as 9,15 %.

Table 4.1. *Normalized ECI of each retrofit measure*

	Activites	Payback Period (Year)			Average Payback Period (Year)	Normalized ECI	Normalized ECI
		Percentile 5	Mean	Percentile 95			
Aydın	1.Retrofit Envelope Insulation	12.523	21.209	43.226	21.635	0.085	3
	2.Retrofit Lighting Retrofit	1.082	3.397	5.002	3.263	0.561	1
	3.Retrofit PV Installation	3.063	5.445	6.470	5.165	0.354	2
	4.Retrofit Heat Recovery Units	undefined	undefined	undefined	undefined	undefined	-
Tekirdağ	1.Retrofit Envelope Insulation	4.704	6.375	7.812	6.308	0.262	2
	2.Retrofit Lighting Retrofit	1.046	3.270	4.801	3.112	0.531	1
	3.Retrofit PV Installation	4.461	8.415	10.312	7.969	0.207	3
	4.Retrofit Heat Recovery Units	undefined	undefined	undefined	undefined	undefined	-
Ankara	1.Retrofit Envelope Insulation	2.461	3.219	3.823	3.164	0,415	1
	2.Retrofit Lighting Retrofit	1.082	3.396	4.999	3.313	0.396	2
	3.Retrofit PV Installation	3.930	7.238	8.753	6.934	0.189	3
	4.Retrofit Heat Recovery Units	undefined	undefined	undefined	undefined	undefined	-
Erzincan	1.Retrofit Envelope Insulation	2.148	2.797	3.310	2.775	0.448	1
	2.Retrofit Lighting Retrofit	1.082	3.396	4.999	3.249	0.382	2
	3.Retrofit PV Installation	4.110	7.629	9.266	7.322	0.170	3
	4.Retrofit Heat Recovery Units	undefined	undefined	undefined	undefined	undefined	-

Based on the result of the analyzes, Table 4.1. shows the average payback period and normalized ECI values in the last two columns, respectively. According to these values, while lighting retrofit has the highest economic impact in the first and second climate regions, envelope insulation has the highest economic impact in the third and fourth climate regions with lower average temperature.

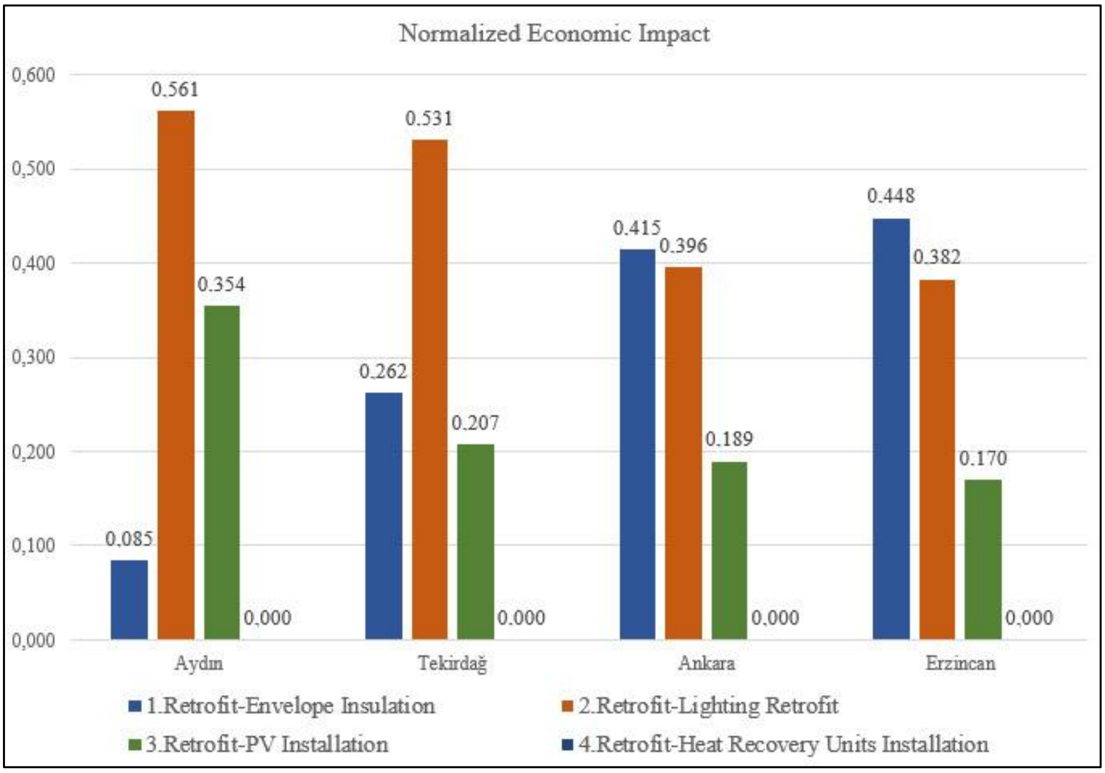


Figure 4.1. Normalized ECI of each retrofit measure

Since, the lighting retrofit implementation is cost-effective and provides high amount of energy saving. However, for the third and fourth climate regions where the heating load is higher, the envelope insulation implementation in these regions provides significant energy saving in terms of heating loads. Therefore, null hypothesis in

Hypothesis III is not accepted. As a result, envelope insulation implementation has the most economic impact for the third and fourth climate regions which are colder climate zones.

On the other hand, the economic impact of heat recovery devices is defined as undefined in the Table 4.4 and it means that there is no positive effect on economic sustainability. Since, the initial investment costs of heat recovery devices are very high compared to other retrofit types. For this reason, considering the ratio of initial investment cost to expected annual energy saving cost (IIC / AECS) and assumed discount rate factor of 9,15%, The result of the payback period equation defined as *n* in Equation 3 is mathematically undefined. As a result, heat recovery devices have no effect on economic sustainability in each climate regions in Turkey and it can be considered as the weakest retrofit type in terms of economic sustainability among the retrofit types.

In conclusion, it can be understood from the Figure 4.1, climates characteristics affects economic sustainability impact of retrofit measures and alternative hypothesis in Hypothesis I is accepted.

4.2. Environmental Impact

Each proposed retrofit type provides a reduction in greenhouse gas emissions as well as energy savings. Equation 5 was used to calculate CO_2-equivalent reduction for each retrofit type. In the Table 4.2., CO_2-equivalent saving and Normalized ECI values were given. In addition, the average energy saving rate provided by the retrofit types in Table 4.2. is summarized. According to this summary table, envelope insulation reduces heating energy load by 34 % while HR device saves around 16 %. Lighting retrofit reduces lighting energy by 40 %. At the same time, the proposed PV panels for this project can meet 53 % of the lighting energy load.

Table 4.2. *Normalized ENI of each retrofit measure*

Cities	Activities	Average emission saving, CO_2-Eq Saving (kg eq. CO_2/Year)	Normalized ENI	Rank
Aydın	1.Retrofit Envelope Insulation	15,807	0.486	1
	2.Retrofit Lighting Retrofit	3,449	0.106	4
	3.Retrofit PV Installation	5,479	0.169	3
	4.Retrofit Heat Recovery Units	9,488	0.239	2
Tekirdağ	1.Retrofit Envelope Insulation	31,185	0.562	1
	2.Retrofit Lighting Retrofit	3,564	0.064	4
	3.Retrofit PV Installation	3,985	0.072	3
	4.Retrofit Heat Recovery Units	16,770	0.302	2
Ankara	1.Retrofit Envelope Insulation	61,404	0.631	1
	2.Retrofit Lighting Retrofit	3,450	0.040	4
	3.Retrofit PV Installation	4,426	0.051	3
	4.Retrofit Heat Recovery Units	23,855	0.277	2
Erzincan	1.Retrofit Envelope Insulation	61,404	0.633	1
	2.Retrofit Lighting Retrofit	3,450	0.036	4
	3.Retrofit PV Installation	4,264	0.044	3
	4.Retrofit Heat Recovery Units	27,882	0.287	2

As shown in the Table 4.2., the rank of each retrofit types is the same for each climate regions. In all climate regions, envelope insulation is the retrofit type that has the most environmental sustainability impact. This retrofit type is followed by heat recovery unit implementation, PV installation and lighting retrofit respectively in terms of CO_2-equivalent saving.

Heating energy consumption constitutes the largest part of the energy consumption in school buildings. For this reason, envelope insulation and heat recovery unit installation which affect the heating load and provide savings in the heating energy consumption are the retrofit types that has more environmental sustainability impact. Therefore, null hypothesis in Hypothesis IV is not accepted.

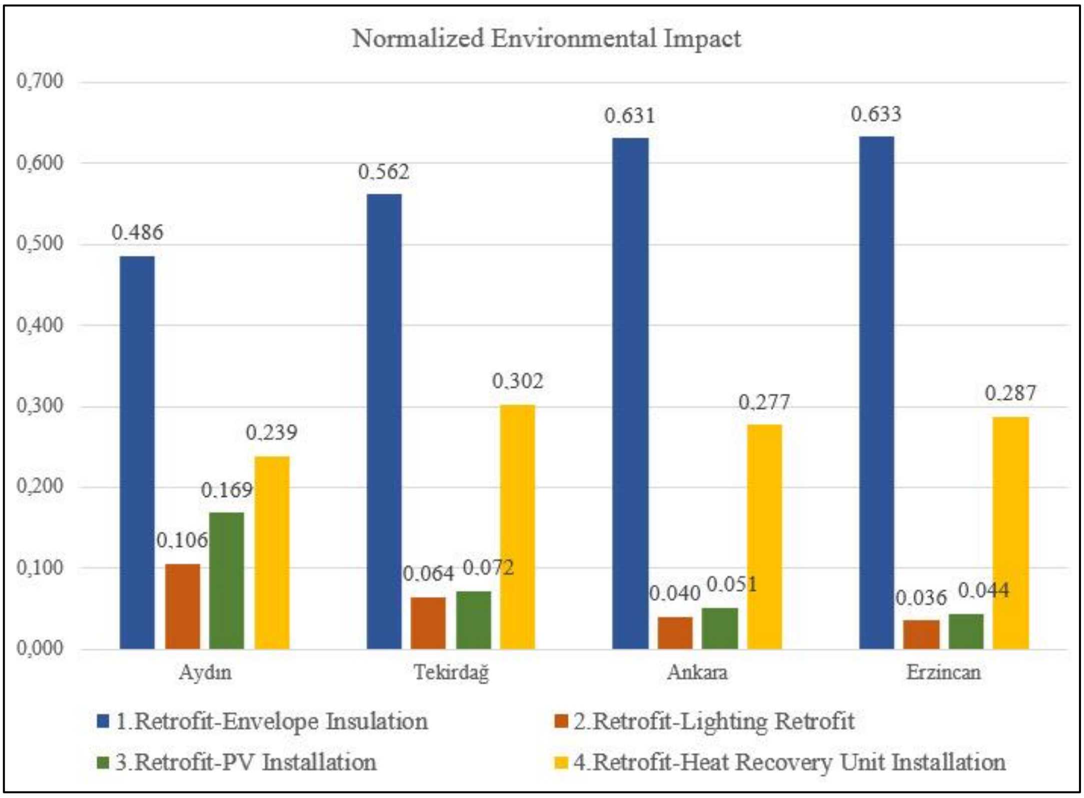


Figure 4.2. Normalized ENI of each retrofit measure

In addition, the electrical load of this building is less than the heating load and the electricity generation capacity of the PV panels is determined according to the electrical demand of the building. Therefore, although it is known that PV panels have a great contribution in terms of renewable energy sources and environmental sustainability, the environmental sustainability effect of PV panel installation for this project is lower than envelope isolation and heat recovery unit installation.

Although the lighting retrofit provides considerable energy savings proportionally, the CO_2-Eq saving is minimal compared to the other retrofit types because of the low electrical energy load for lighting system. As a result, retrofit type lighting retrofit which has the least environmental sustainability effect.

In conclusion, it can be understood from the Figure 4.4., there is a direct relation between climate types and environmental sustainability of retrofit measures. Thus, climates characteristics affects environmental sustainability impact of retrofit measure and alternative hypothesis in Hypothesis II is accepted.

4.3. Social Impact

Proposed retrofit measures have also impact on sustainability and for evaluation of the sustainability assessment of each retrofitting measure, survey is proper a method (Jafari & Valentin, 2017). In this research, the target population of this survey study is the educators who are active users of the school buildings. For this reason, METU Faculty of Education Faculty Members and Research Assistants and, Teachers of the METU Development Foundation School were sent survey invitation by e-mail. A total of 219 people was sent an e-mail and 31 of these participated and answered the survey questions.

With the Question 1 of the survey, Equation 6 was used and RII of the social benefits were calculated. According to these measures, the health is the most important social benefits of the energy retrofit measure (RII health=0,994). Productivity is the second (RII productivity =0,981) and comfort & satisfaction is the third important social benefit of the retrofitting measure (RII comfort & satisfaction =0,981).

Table 4.3. *Normalized SOI of each retrofit measure*

Measure	Activites	Health	Comfort& Satisfaction	Productivity	Social Impact Index (SII)	Normalized SOI	Rank
		Relative Importance Index (RII)					
		0.994	0.852	0.981			
		Social Impact Factor (IF)					
Envelope	1.Retrofit Envelope Insulation	0.884	0.865	0.871	0.823	0.256	2
Electrical	2.Retrofit Lighting Retrofit	0.800	0.858	0.890	0.800	0.249	3
Renewable Energy	3.Retrofit PV Installation	0.910	0.755	0.613	0.716	0.223	4
Mechanical	4.Retrofit Heat Recovery Units	0.968	0.890	0.935	0.879	0.273	1

For assessing the energy retrofitting impact on social benefits, Equation 9 was calculated according to participants answers of Question 2. As shown in the Table 4.3., IF of each retrofit on social benefits are defined. According to the results, envelope insulation, heat recovery units and PV panel installation are most effective on health factor, while lighting retrofit affects the productivity.

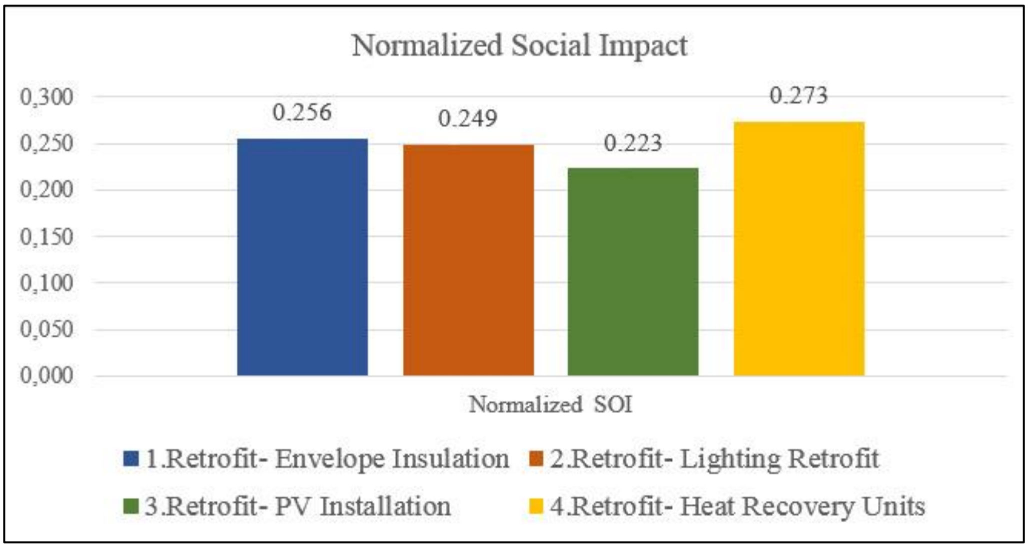


Figure 4.3. Normalized SOI of each retrofit measure

After calculation of the social IF, by using Equation 11, SII and normalized SOI was calculated. According to results, while heat recovery unit installation has the highest social impact and it is followed by envelope insulation installation, lighting retrofit and PV panel installation respectively.

4.4. Sustainability Impact

According to Equation 12, the normalized impact factors of each retrofitting measure in terms of economic, environmental and social criteria was multiplied with the weight factors of different scenario (Table 3.9.). Sustainable impact of each retrofitting measure was calculated for each scenario: scenario giving equal importance to all criteria (1), economic scenario (2), environmental scenario (3) and, social scenario (4) and results are shown in the Table 4.4.

Table 4.4. *Sustainability impact of each retrofit measure*

	Measure	Equal Importance Scenario		Economic Scenario		Environmental Scenario		Social Scenario	
		Index	Rank	Index	Rank	Index	Rank	Index	Rank
1. Region Aydın	1.Retrofit Envelope Insulation	0.273	2	0.142	3	0.423	1	0.262	2
	2.Retrofit Lighting Retrofit	0.302	1	0.484	1	0.166	4	0.266	1
	3.Retrofit PV Installation	0.246	3	0.323	2	0.193	3	0.230	3
	4.Retrofit Heat Recovery Units	0.169	4	0.051	4	0.219	2	0.242	4
2. Region Tekirdağ	1.Retrofit Envelope Insulation	0.356	1	0.291	2	0.501	1	0.287	1
	2.Retrofit Lighting Retrofit	0.278	2	0.456	1	0.129	3	0.258	2
	3.Retrofit PV Installation	0.166	4	0.195	3	0.100	4	0.206	4
	4.Retrofit Heat Recovery Units	0.190	3	0.058	4	0.269	2	0.249	3
3. Region Ankara	1.Retrofit Envelope Insulation	0.430	1	0.420	1	0.572	1	0.309	1
	2.Retrofit Lighting Retrofit	0.226	2	0.346	2	0.097	3	0.242	2
	3.Retrofit PV Installation	0.153	4	0.179	3	0.082	4	0.202	4
	4.Retrofit Heat Recovery Units	0.182	3	0.055	4	0.249	2	0.246	3
4. Region Erzurum	1.Retrofit Envelope Insulation	0.441	1	0.447	1	0.577	1	0.313	1
	2.Retrofit Lighting Retrofit	0.220	2	0.334	2	0.092	3	0.241	2
	3.Retrofit PV Installation	0.144	4	0.162	3	0.074	4	0.199	4
	4.Retrofit Heat Recovery Units	0.185	3	0.056	4	0.257	2	0.247	3

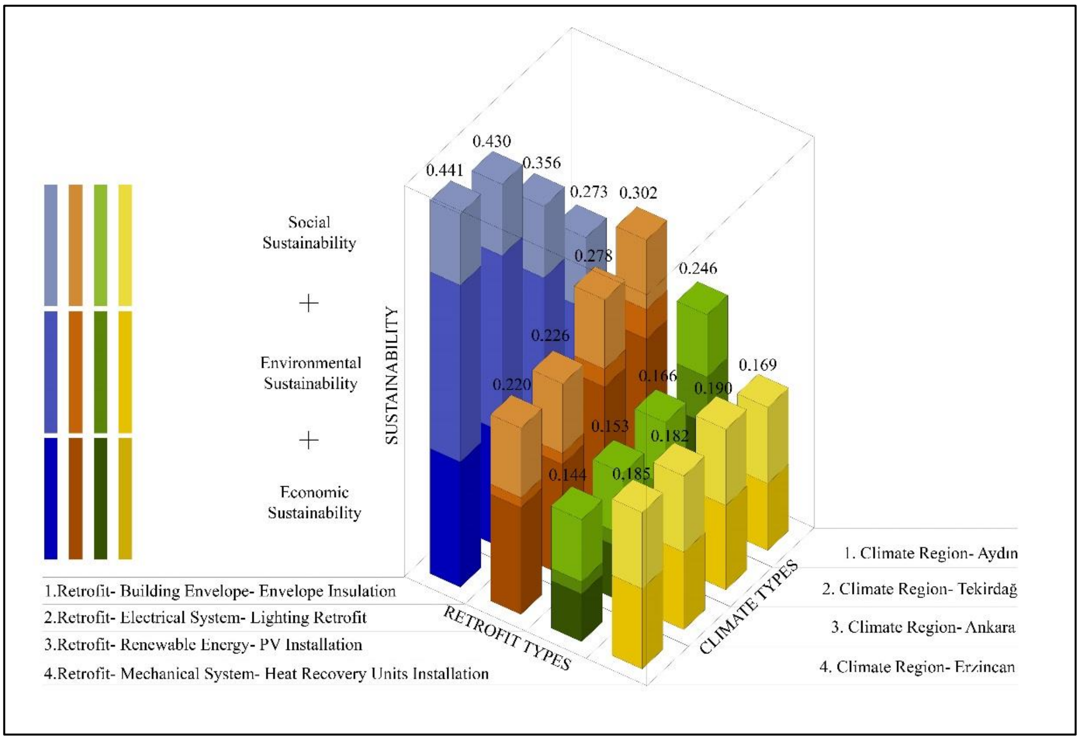


Figure 4.4. Sustainability impact matrices according to equal importance scenario

According to scenario giving equal importance to all criteria, while lighting retrofit has the highest sustainability impact for first climate region; envelope insulation has the highest sustainability impact for the other climate types. At the same time, it is seen that the order of sustainability impact of retrofit measures is the same in these 3 climate regions when compared in terms of ranking. In this order, the envelope insulation is followed by lighting retrofit, heat recovery unit installation and PV installation.

In the first climate region, lighting retrofit is followed by envelope insulation, PV panel installation and heat recovery unit installation respectively. It is important to note that the sustainability impact of PV panel installation and envelope insulation is different from the other climate regions in first climate region. While the sustainability impact of PV panel installation increased in the first climate region, the sustainability impact of the envelope insulation was lost in the first climate region.

According to the economic scenario, the most sustainable effect has the lighting retrofit in the first and second climate regions, while in the third and fourth climate regions envelope insulation has the most sustainability impact. Although lighting retrofit has the most sustainability impact in the first and second climate region, the rank of the other retrofit types is different in these climate regions. While lighting retrofit in first climate region followed by PV panel installation, envelope insulation and heat recovery unit installation; in second climate region lighting retrofit is followed by envelope insulation, PV panels installation and heat recovery unit installation.

In the environmental scenario, the two types of retrofits, which have the most sustainability effect for all regions, are respectively building envelope insulation and heat recovery unit installation. Furthermore, unlike other regions, PV panel installation has more sustainability effect than lighting retrofit in Climate Region I.

The results in social scenario are parallel to the scenario giving equal importance to all criteria. Since, the social sustainability impact of each retrofit measures are assumed to be the same for all regions and the climate factor could not be considered in the social survey

.

CHAPTER 5

CONCLUSION

In this chapter, summary of this research study presented initially. After that main results and discussions are stated and the limitation of this study is also explained. Finally, the recommendation for further studies about sustainability impact assessment is also examined.

5.1. Research Summary

Considering the existing building conditions, the importance of sustainability and energy efficiency for these buildings is increasing day by day. One of the existing building types is school buildings and the school buildings are special buildings where future generations are educated in. In Turkey, there are many types of school projects made before the 2000s and a large part of these school buildings need to be improved in terms of sustainability and energy efficiency.

There are many studies in the literature about sustainability and sustainability assessment. Most of these studies focus on economic and environmental sustainability, and there are only a few studies on social sustainability. An important part of the studies on sustainability and energy efficiency is on energy retrofit strategies. However, in the literature there is no study related to sustainability impact of retrofit measure in different climate regions.

Considering the necessity of a study that demonstrates the sustainability impact of retrofit types in different climates, this study is aimed to evaluate sustainability impact of the proposed retrofit measures on type school projects in four different climate types of Turkey. Therefore, information was collected about Ayrancı Anatolian High School in Ankara (Climate Region III) which is an example of the type 735 school project and the samples of the type 735 project in other climate regions were determined.

Based on the case project, the potentials and shortcomings of these school buildings were determined, and 4 different retrofitting measure were proposed: (1) building envelope insulation, (2) lighting retrofit, (3) PV panel installation and (4) heat recovery unit installation.

In order to evaluate four different retrofit studies and four different climate types, 16 different cases were created in this research study. These cases were evaluated in terms of economic, environmental and social sustainability based on the guidelines outlined by Jafari and Valentine (Jafari & Valentin, 2017). At the end, the results of the sustainability effect of retrofit types in different climates are presented and examined comparatively.

5.2. Main Results and Discussion

The main purpose of this study is to evaluate the sustainability effect of proposed retrofit types in different climates and in this respect, it is concluded that retrofit types have different sustainability effects in different climates as a result of analyzes and calculations on case studies. The main results of this study are listed below:

- Economic Sustainability Impact: The ratio between the initial investment cost of retrofit measure and the energy savings that it provides is very important in terms of economic sustainability. In this respect, for each climate zone, heat recovery unit installation is not economically sustainable because of the high initial investment cost. At the same time, lighting retrofit is the retrofit type that has the lowest payback period in Climate Region I and II. Therefore, in Climate Regions I and II, lighting retrofit has the highest economical sustainability impact. (Figure 4.1.)

In addition, envelope insulation has the most economic sustainability effect in climate regions III and IV where the heating load is more than the other regions.

• Environmental Sustainability: Environmental sustainability is directly related to amount of energy saving that is provided by energy retrofit types. Retrofit types affect heating load that is highest energy load, saves more energy. Therefore, envelope insulation has the most environmental sustainability impact. Considering the climate types, envelope insulation has the most environmental impact in each climate regions. At the same time, heat recovery unit installation has much more impact than lighting retrofit and PV panel installation on environmental sustainability in each climatic region.

• Social Sustainability Impact: According to survey result, health is the most important social benefits of the energy retrofit measures for school buildings and it is followed by productivity and comfort & satisfaction respectively. In addition, while lighting retrofit affects the productivity, envelope insulation, heat recovery units and PV panel installation are most effective on health factor. Envelope insulation has the highest social impact and it is followed by heat recovery unit installation, lighting retrofit and PV panel installation respectively.

• Sustainability Impact: According to equal importance scenario, except the Climate Region I, envelope insulation is the retrofit hat the highest sustainability impact. As a result, it can be said that envelope insulation is very critical to develop sustainability for school building and envelope insulation is primary retrofit type for Climate Regions II, III and IV. In addition to this lighting retrofit is very reasonable and appropriate retrofit type for each climate regions. Using renewable energy resources is very important for increasing sustainability and increasing awareness about sustainability. However, according to numeric values of the Table 4.4 and Figure 4.4, sustainability impact rank of the PV panel installation is 3 or 4. It means that because of the lower electrical energy consumption and high initial investment cost, renewable energy sources is not the primary retrofit types for school buildings.

Although, it is known that the heat recovery units are important for the improvement of the indoor air quality; in terms of sustainability impact, HR is not a primary or secondary priority for any climate zone. (Figure 4.4)

5.3. Limitation of The Study

This study has some limitations in the process of sustainability assessment.

Firstly, to provide more accurate comparison of climate types, it was assumed that type 735 school project in Climate Region I, II and IV has the same orientation (north-east) of Ayrancı Anatolian High School in Ankara (case study-Climate Region II). Orientation of schools and its effect on sustainability impact of retrofit may be considered for examining real case studies.

Secondly, some cost inputs such as maintenance cost, operational cost and tax rebate have been neglected in the calculation method used for evaluating of economic sustainability impact. Therefore, neglected values should be considered for a more accurate and more precise payback analysis.

Thirdly, in this study, retrofit types that is required for four climate regions were selected. Retrofits related to cooling requirement were not included in this study since the cooling requirement is not required for all climatic zones.

Finally, in the survey study on social sustainability impact of retrofit types, the climate impact was neglected. Since, this survey is not conducted for participants in different climatic zones and the questions were focused on the retrofit types impact on social sustainability.

5.4. Recommendation for Further Studies

The purpose of this study is to assess the sustainability impact of the retrofit measures implemented to the existing type school buildings in different climatic zones. However, in this evaluation process, only proposed energy retrofit studies such as envelope insulation, lighting retrofit, PV installation and heat recovery unit installation have been evaluated.

For this reason, in future studies, potentials and deficiencies of such school buildings can be examined in more detail. As a result of these investigations, the range of retrofit studies can be extended and retrofit strategies can be made more comprehensive.

At the same time, different project types with different orientations can also be analyzed as case studies. As a result, a research framework can be extended in which alternatives are increased and orientation factor is also considered.

Considering the limitation in this study, retrofit types can be increased for the type school project and a comprehensive climate-based retrofit guideline can be created, where orientation factors are evaluated with more precise measurements.

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APPENDICES

A. Survey Questions in English

Survey on The Effect of Energy Retrofit Measurements on Social Sustainability in School Building

The school buildings, which the educators and students spend in a very large part of the day, differentiate from other building types in terms of user profile and function. In this study, the effects of actions to improve energy efficiency in school buildings on social sustainability factors (health, comfort and efficiency) will be analyzed.

Section A1:

1) Educators and students spend most of their days in class. What is your expectation from the classroom environment as users of a classroom environment? Rate the significance level of the following sequential factors for you from 1 to 5. (5: very important, 4: important, 3: moderately important, 2: less important, 1: very important)

	1	2	3	4	5
-Classroom environment provides a healthy working environment	☐	☐	☐	☐	☐
-Comfortable classroom environment	☐	☐	☐	☐	☐
-Increasing the working efficiency of the classroom environment	☐	☐	☐	☐	☐

Section A2:

1) How much the effect of appropriate temperature in the classroom environment on your health, comfort and working efficiency has? Mark. (5: has very strong effect 4: has strong effect 3: has moderate effect 2: has little effect 1: has very little effect)

	1	2	3	4	5
-Impact on your health	☐	☐	☐	☐	☐
-Impact on your comfort	☐	☐	☐	☐	☐
-Impact on your productivity	☐	☐	☐	☐	☐

2) How much the effect of appropriate lighting in the classroom environment on your health, comfort and productivity has? Mark. (5: has very strong effect 4: has strong effect 3: has moderate effect 2: has little effect 1: has very little effect)

	1	2	3	4	5
-Impact on your health	☐	☐	☐	☐	☐
-Impact on your comfort	☐	☐	☐	☐	☐
-Impact on your productivity	☐	☐	☐	☐	☐

3) How much the effect of air quality in the classroom environment on your health, comfort and productivity has? Mark. (5: has very strong effect 4: has strong effect 3: has moderate effect 2: has little effect 1: has very little effect)

	1	2	3	4	5
-Impact on your health	☐	☐	☐	☐	☐
-Impact on your comfort	☐	☐	☐	☐	☐
-Impact on your productivity	☐	☐	☐	☐	☐

4) How much impact do you have on health, comfort and productivity factors when evaluating the use of solar energy in school buildings from a social and global perspective? (5: has very large effect, 4: has great effect, 3: has moderate effect, 2: less has the effect, 1: has little effect)

	1	2	3	4	5
-Impact on your health	☐	☐	☐	☐	☐
-Impact on your comfort	☐	☐	☐	☐	☐
-Impact on your productivity	☐	☐	☐	☐	☐

B. Survey Questions in Turkish

Okul Yapılarında Enerji İyileştirmesine Yönelik Çalışmaların Sosyal Sürdürebilirlik Üzerine Etkisi Konulu Anket Çalışması

Eğitimcilerin ve öğrencilerin gününün çok büyük bir kısmını içerisinde geçirdiği okul yapıları, sürdürebilirlik açısından değerlendirildiğinde kullanıcı profili ve fonksiyonu yönüyle diğer yapı türlerinden ayrışmaktadır. Bu çalışmada okul yapılarında enerji verimliliğini sağlamak amacıyla yapılan enerji iyileştirmesine yönelik eylemlerin sosyal sürdürebilirlik faktörleri (sağlık, konfor ve verimlilik) üzerindeki etkisi analiz edilecektir.

Bölüm A1:

1) Eğitimciler ve öğrenciler günlerinin çok büyük bir kısmını sınıfta geçirmekteler. Bu doğrultuda bir sınıf ortamının kullanıcıları olarak sınıf ortamından beklentiniz ne yöndedir? Sizin için aşağıdaki sıralı faktörlerin önemlilik derecesini 1 ile 5 arasında derecelendiriniz. (5: çok önemli, 4: önemli, 3: orta derecede önemli, 2:az önemli, 1: çok az önemli)

	1	2	3	4	5
-Sınıf ortamının sağlıklı bir çalışma ortamı sağlaması	☐	☐	☐	☐	☐
-Sınıf ortamının konforlu olması	☐	☐	☐	☐	☐
-Sınıf ortamının çalışma verimini arttırıcı olması	☐	☐	☐	☐	☐

Bölüm A2:

1) Sınıf ortamında uygun sıcaklığın sağlanmasının sağlığınızın, konforunuzun ve çalışma verimliliğinizin üzerinde ne kadar etkisi vardır, işaretleyiniz. (5: çok büyük etkisi vardır 4: büyük etkisi vardır 3: orta derecede etkisi vardır 2: az etkisi vardır 1: çok az etkisi vardır)

	1	2	3	4	5
- Sağlığınız üzerindeki etkisi	☐	☐	☐	☐	☐
- Konforunuz üzerindeki etkisi	☐	☐	☐	☐	☐
- Çalışma veriminiz üzerindeki etkisi	☐	☐	☐	☐	☐

2) Sınıf ortamında uygun ışığın sağlanmasının sağlığınızın, konforunuzun ve çalışma veriminizin üzerinde ne kadar etkisi vardır? (5: çok büyük etkisi vardır, 4: büyük etkisi vardır, 3: orta derecede etkisi vardır, 2: az etkisi vardır, 1: çok az etkisi vardır)

	1	2	3	4	5
- Sağlığınız üzerindeki etkisi	☐	☐	☐	☐	☐
- Konforunuz üzerindeki etkisi	☐	☐	☐	☐	☐
- Çalışma veriminiz üzerindeki etkisi	☐	☐	☐	☐	☐

3) Sınıf ortamında uygun hava kalitesinin sağlanmasının sağlığınızın, konforunuzun ve çalışma veriminizin üzerinde ne kadar etkisi vardır? (5: çok büyük etkisi vardır, 4: büyük etkisi vardır, 3: orta derecede etkisi vardır, 2: az etkisi vardır, 1: çok az etkisi vardır)

	1	2	3	4	5
- Sağlığınız üzerindeki etkisi	☐	☐	☐	☐	☐
- Konforunuz üzerindeki etkisi	☐	☐	☐	☐	☐
- Çalışma veriminiz üzerindeki etkisi	☐	☐	☐	☐	☐

4) Okul yapılarında güneş enerjisinin kullanılmasını toplumsal ve küresel açıdan değerlendirdiğinizde sağlık, konfor ve verimlilik faktörleri üzerinde ne kadar etkisi vardır? (5: çok büyük etkisi vardır, 4: büyük etkisi vardır, 3: orta derecede etkisi vardır, 2: az etkisi vardır, 1: çok az etkisi vardır)

- Sağlığınız üzerindeki etkisi

- Konforunuz üzerindeki etkisi

- Çalışma veriminiz üzerindeki etkisi

1	2	3	4	5
☐	☐	☐	☐	☐
☐	☐	☐	☐	☐
☐	☐	☐	☐	☐

C. Survey Results

Table A.1. *Survey Results*

PARTICIPANTS	QUESTION1			QUESTION2			QUESTION3			QUESTION4			QUESTION5		
	LEVEL OF IMPORTANCE			LEVEL OF IMPACT											
				1.RETROFIT			2.RETROFIT			4.RETROFIT			3.RETROFIT		
	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity
P1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P2	5	5	5	3	4	4	3	3	4	4	3	3	4	4	4
P3	5	4	5	5	4	5	5	3	5	5	5	5	5	4	5
P4	5	4	4	5	4	4	5	4	4	4	4	4	5	5	5
P5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P6	5	5	5	5	3	5	5	4	5	5	5	5	5	5	5
P7	5	5	5	5	4	5	4	5	5	5	4	3	5	5	5
P8	5	4	5	3	3	4	3	4	4	4	4	4	3	4	4
P9	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P10	5	3	5	5	2	5	5	2	5	5	3	3	5	5	5
P11	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P12	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P13	5	5	5	4	4	4	3	4	5	5	3	4	5	5	5
P14	5	5	5	5	5	4	3	2	3	4	3	3	5	5	5
P15	5	5	5	5	5	4	3	4	3	4	3	3	4	5	3
P16	5	5	5	4	4	3	4	4	3	4	4	3	4	4	3
P17	5	4	5	5	5	5	5	5	4	5	5	5	5	5	5
P18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
P19	5	3	4	3	5	4	3	5	4	5	4	1	5	4	4
P20	4	2	5	2	5	4	2	4	5	4	5	2	5	4	3
P21	5	3	5	4	4	5	4	3	5	2	3	2	5	3	5
P22	5	3	4	3	5	5	3	4	5	5	3	1	5	4	5
P23	5	2	5	4	5	4	3	5	5	4	3	2	5	3	4
P24	5	5	5	5	4	4	3	4	5	5	3	1	5	4	5
P25	5	4	5	5	4	4	3	5	4	5	3	2	5	4	5
P26	5	4	5	5	4	3	4	5	5	4	3	2	5	4	5
P27	5	5	5	4	4	4	5	5	4	5	3	1	5	4	5
P28	5	4	5	4	5	5	5	4	5	5	4	1	5	5	5
P29	5	5	5	5	4	4	3	5	4	4	3	2	5	4	5
P30	5	4	5	5	4	3	4	5	3	4	2	2	5	4	5
P31	5	4	5	4	4	4	4	5	4	5	2	1	5	5	5

D. METU Applied Ethics Research Center Survey Approval

UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

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Sayı: 28620816 / 251

10 Mayıs 2019

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Dr.Öğretim Üyesi Koray PEKERİÇLİ

Danışmanlığını yaptığınız **Jülide Arzu ULUÇAY'ın "Okul Yapılarında Enerji İyileştirilmesine Yönelik Çalışmaların Sosyal Sürdürebilirlik Üzerine Etkisi Konulu Anket Çalışması"** başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülmüş ve **239-ODTÜ-2019** protokol numarası ile onaylanmıştır.

Saygılarımızla bilgilerinize sunarız.

Prof. Dr. Tülin GENÇÖZ

Başkan

Prof. Dr. Tolga CAN

Üye

Doç.Dr. Pınar KAYGAN

Üye

Dr. Öğr. Üyesi Ali Emre TURGUT

Üye

Dr. Öğr. Üyesi Şerife SEVİNÇ

Üye

Dr. Öğr. Üyesi Müge GÜNDÜZ

Üye

Dr. Öğr. Üyesi Süreyya Özcan KABASAKAL

Üye

Figure A.1. Certificate of approval from The Applied Ethics Research Center

E. Design Builder Energy Models Data

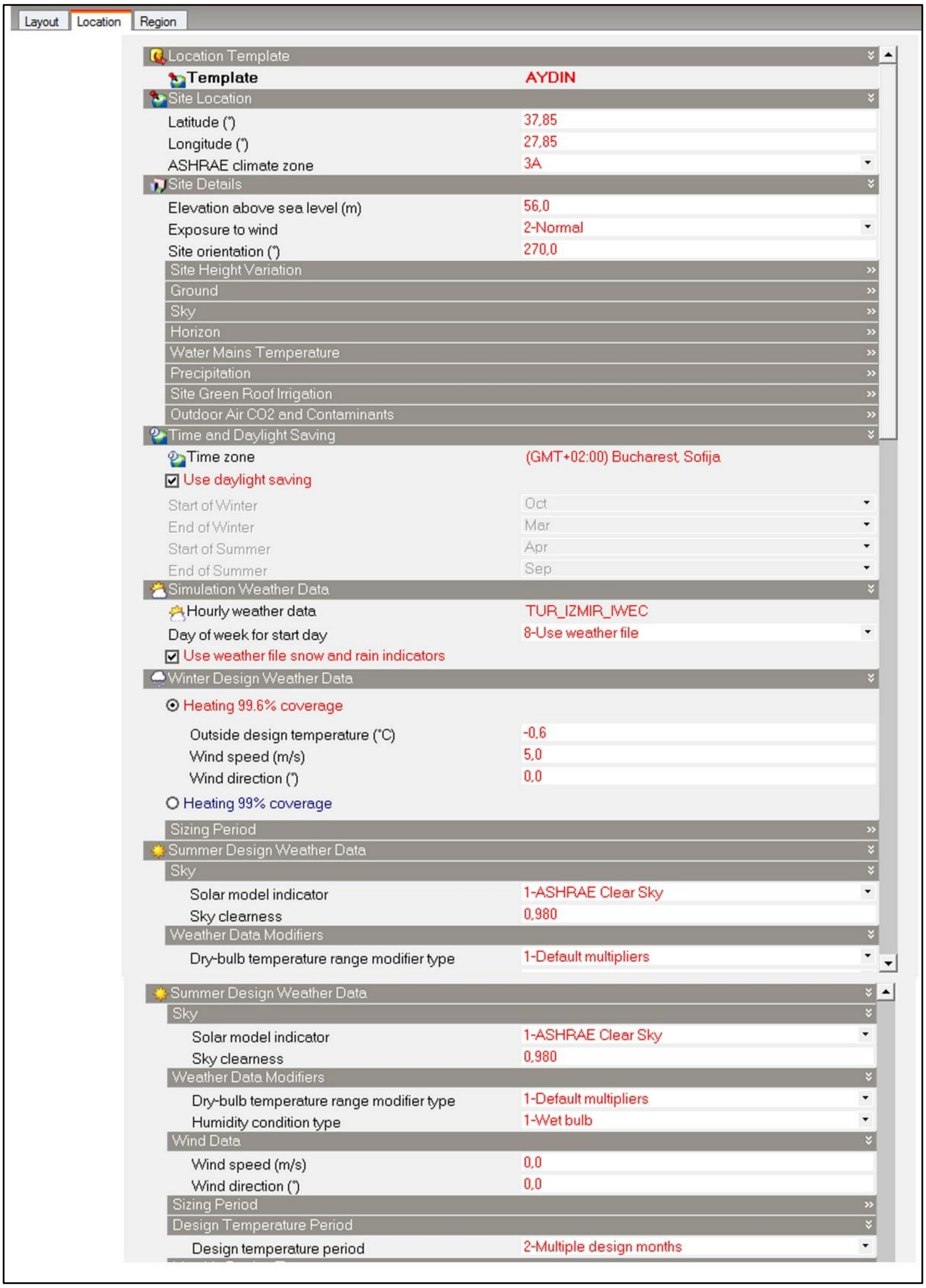

Figure A.2. Model location data of buildings in Aydın

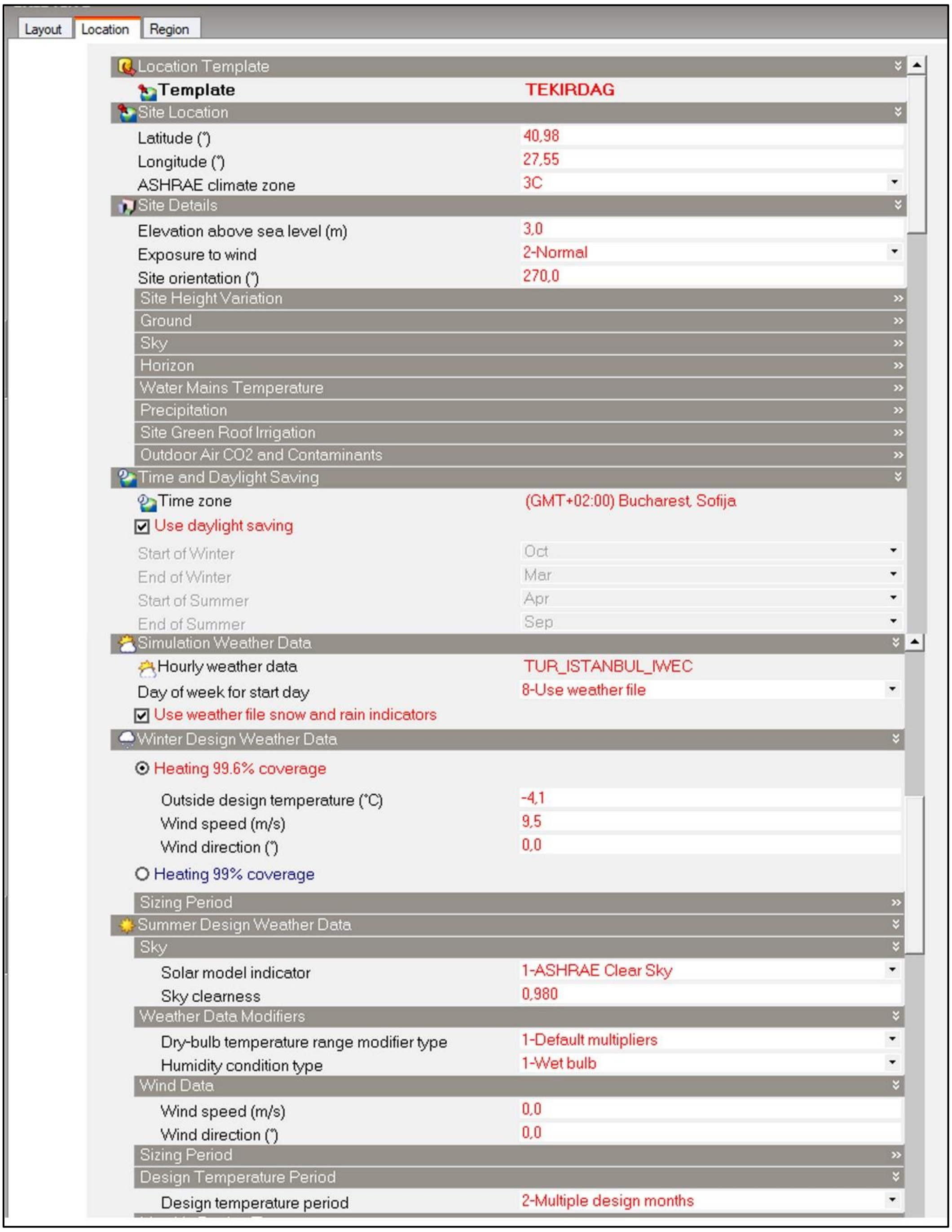

Figure A.3. Model location data of buildings in Tekirdağ

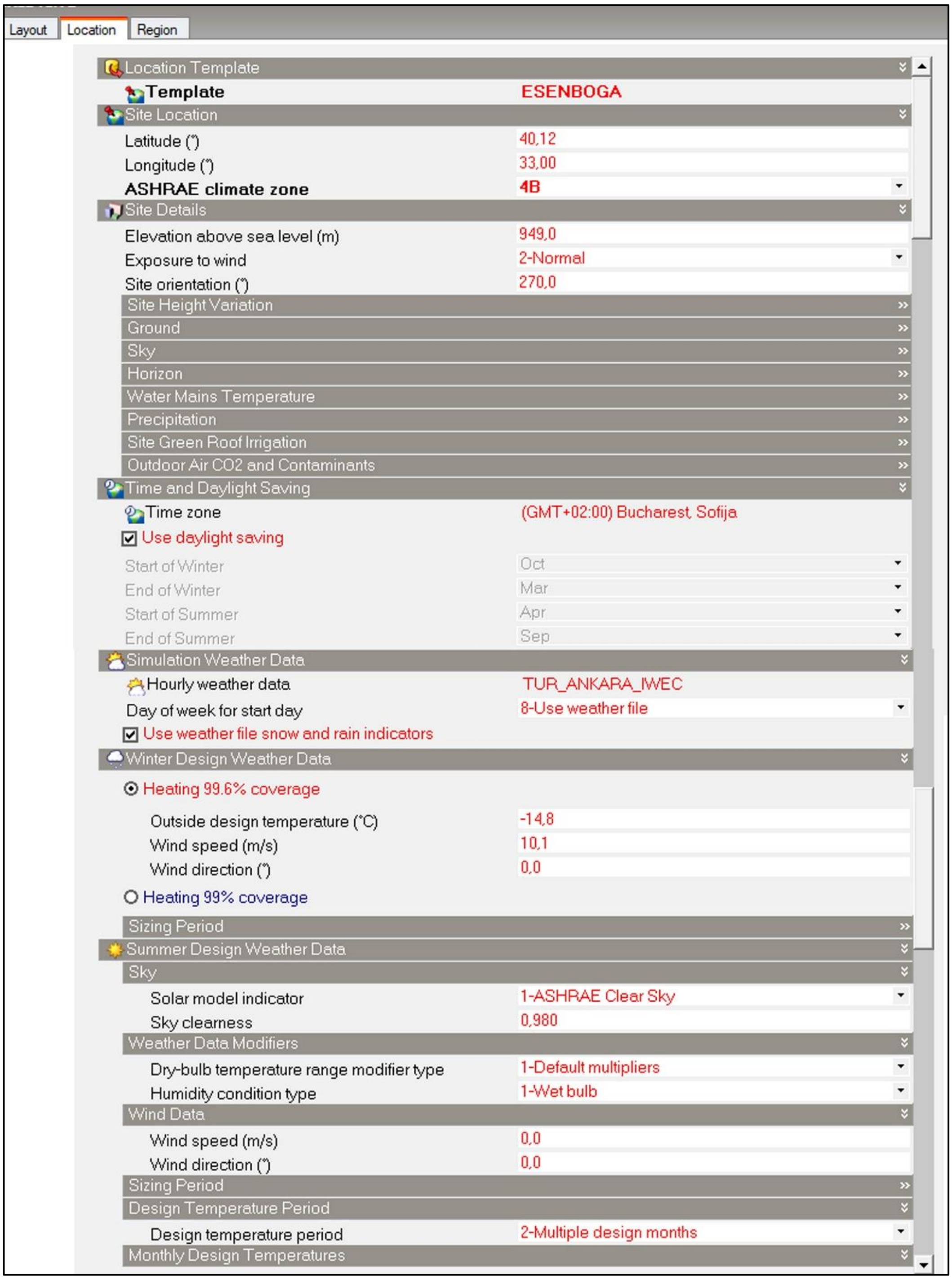

Figure A.4. Model location data of buildings in Ankara

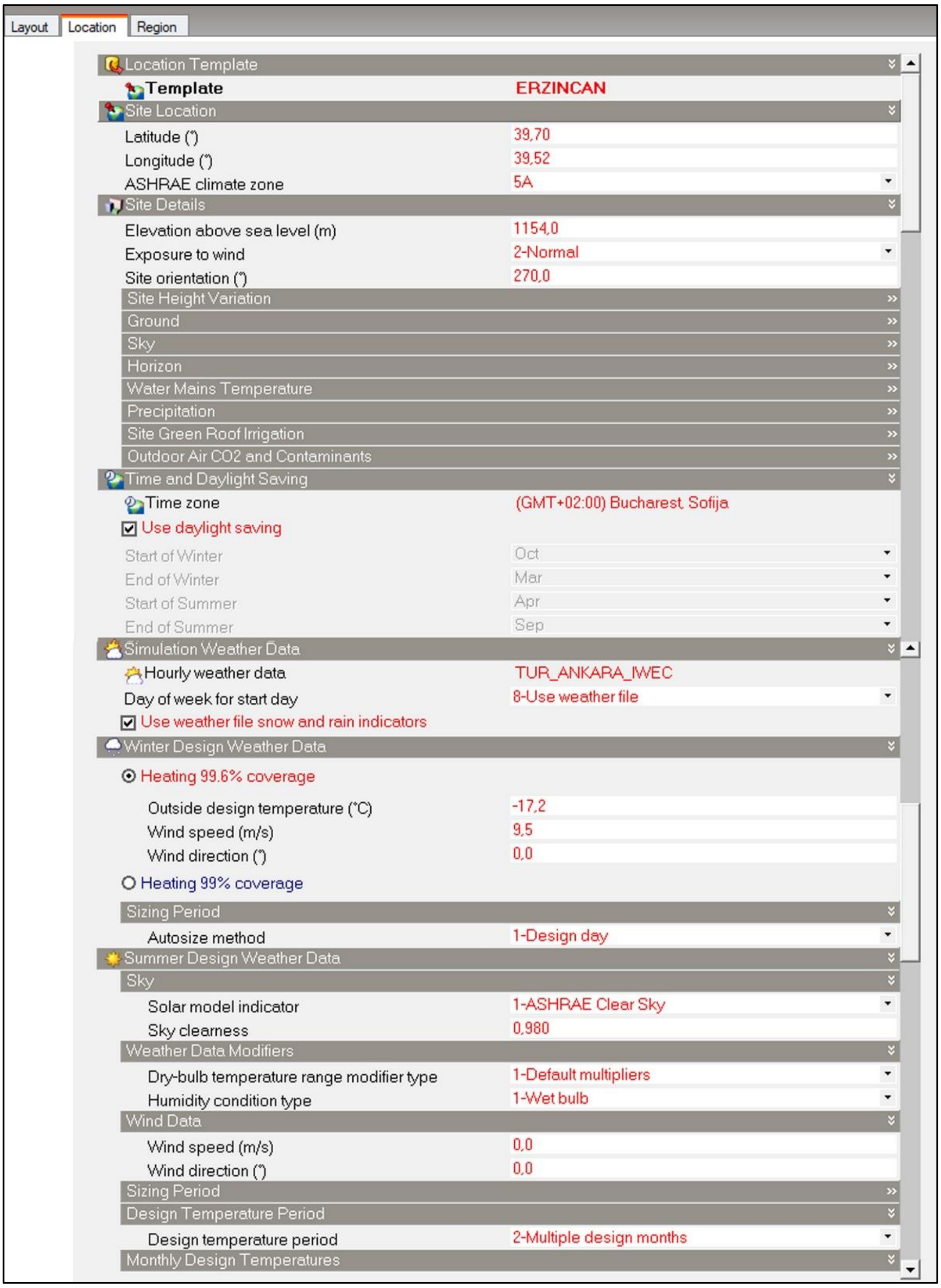

Figure A.5. Model location data of buildings in Erzincan

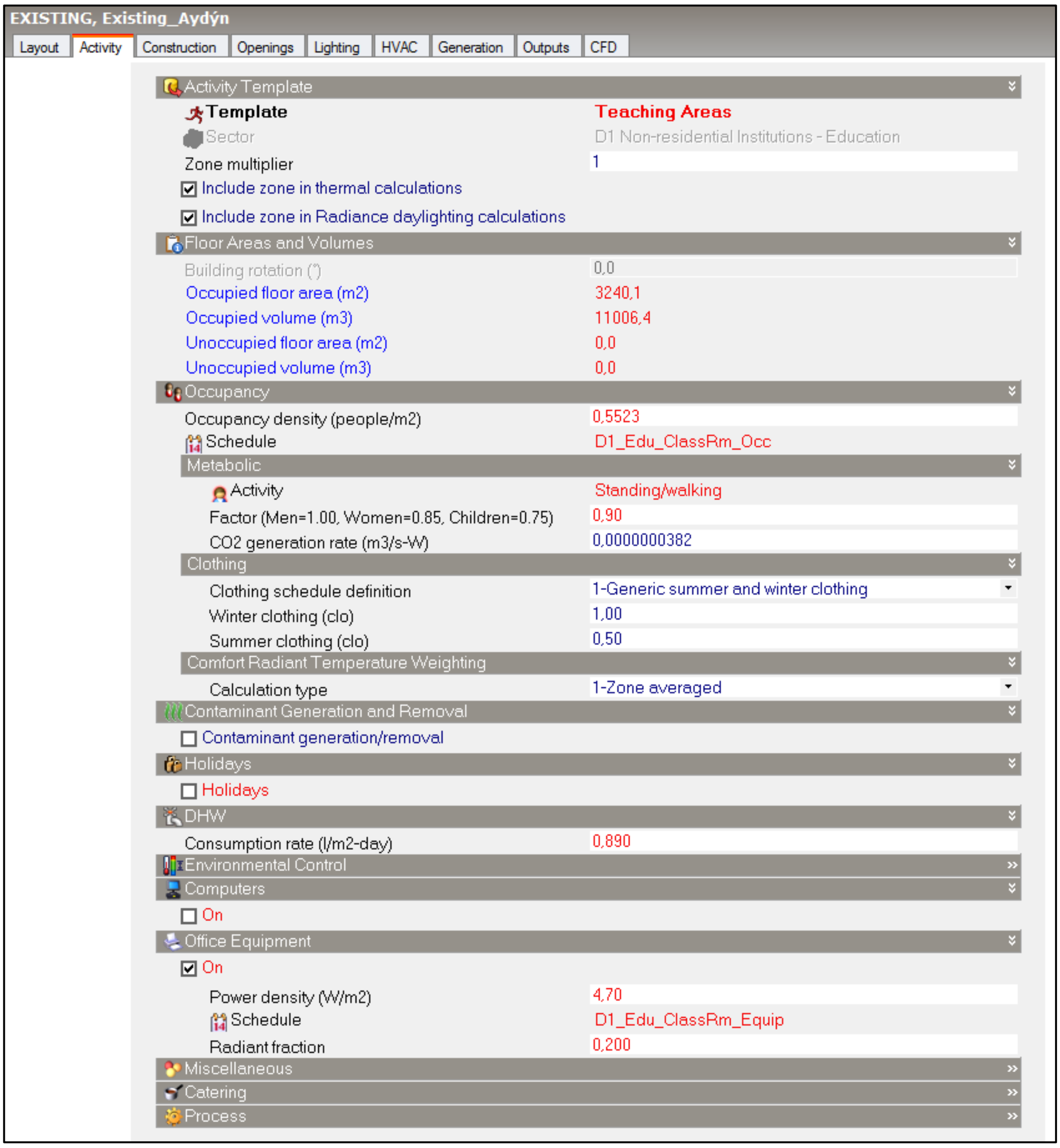

Figure A.6. Model activity data of existing buildings

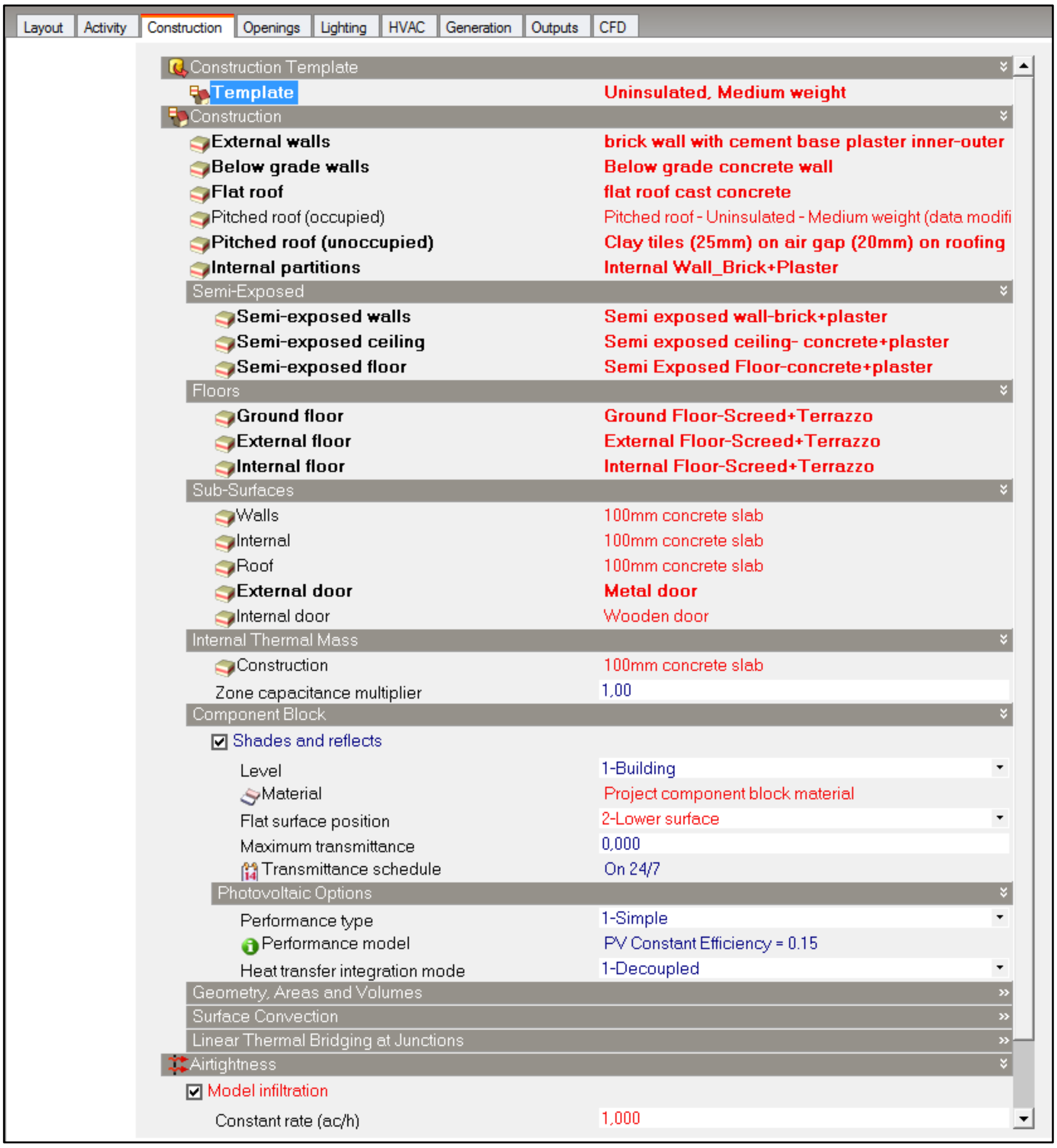

Figure A.7. Model construction data of existing buildings

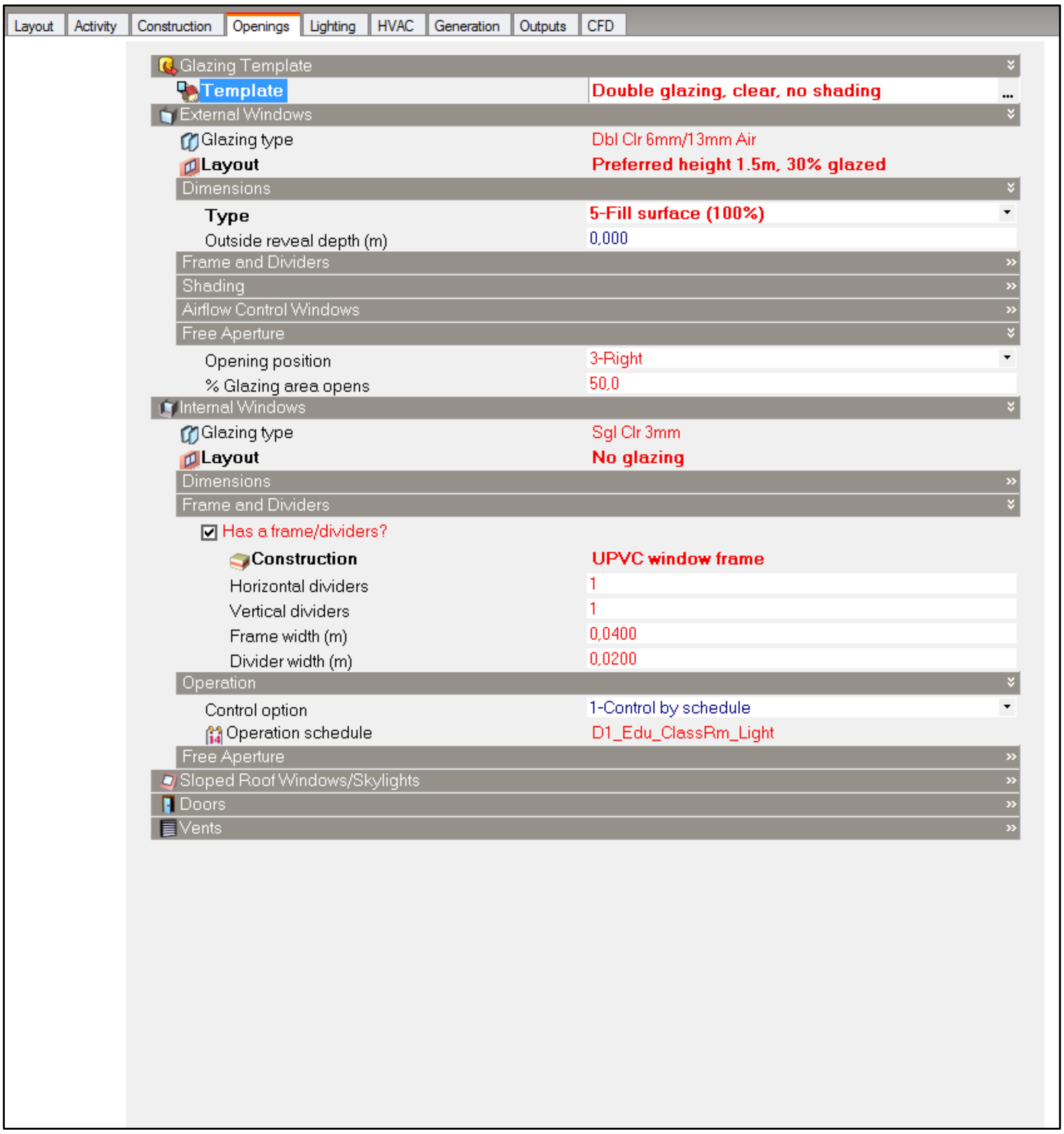

Figure A.8. Model openings data of existing buildings

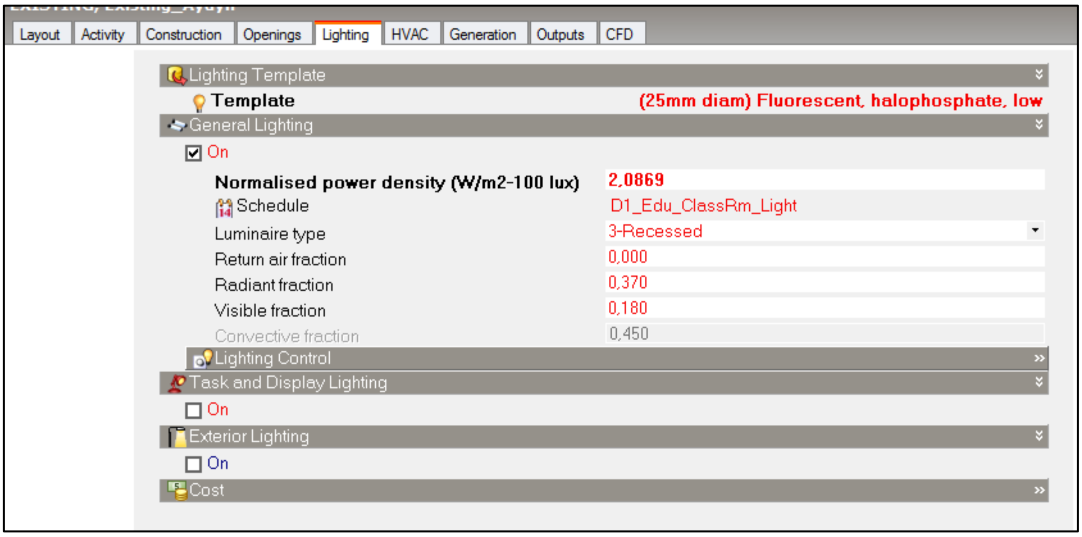

Figure A.9. Model lightings data of existing buildings

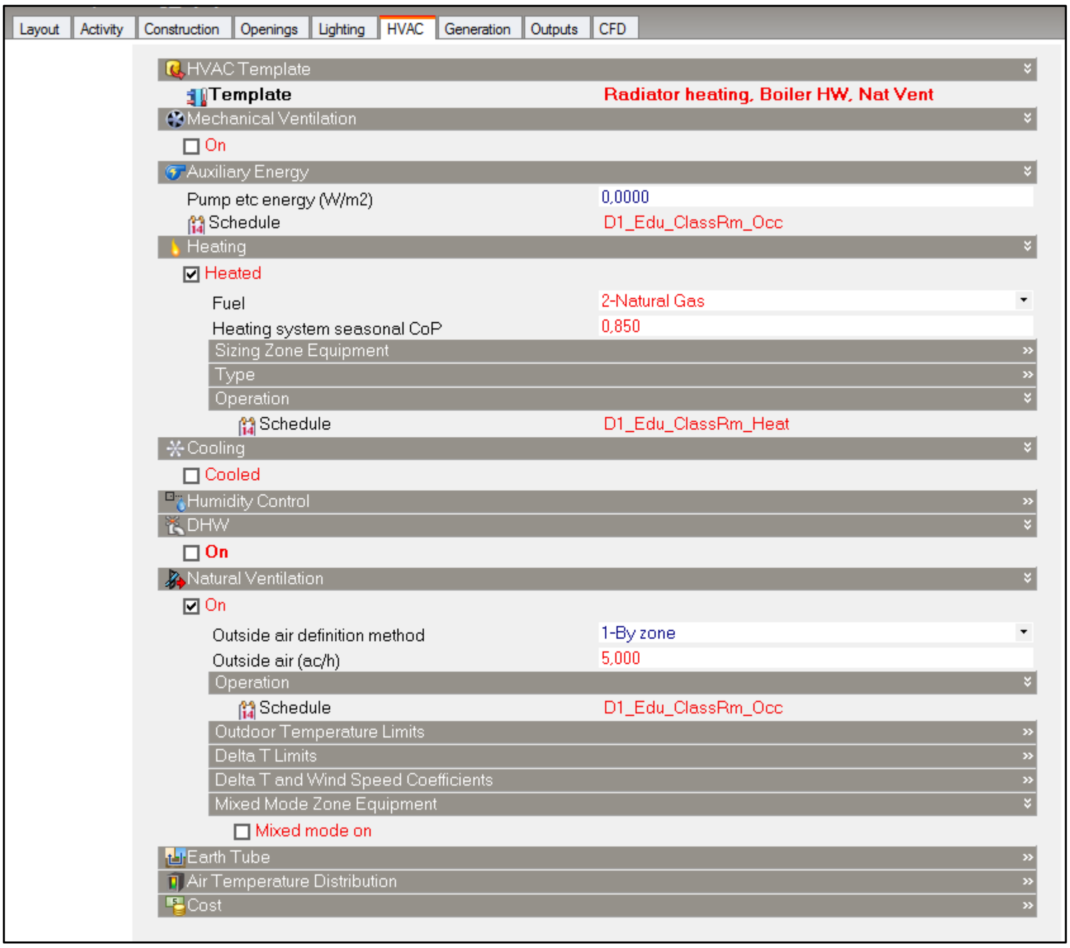

Figure A.10. Model HVAC data of existing buildings

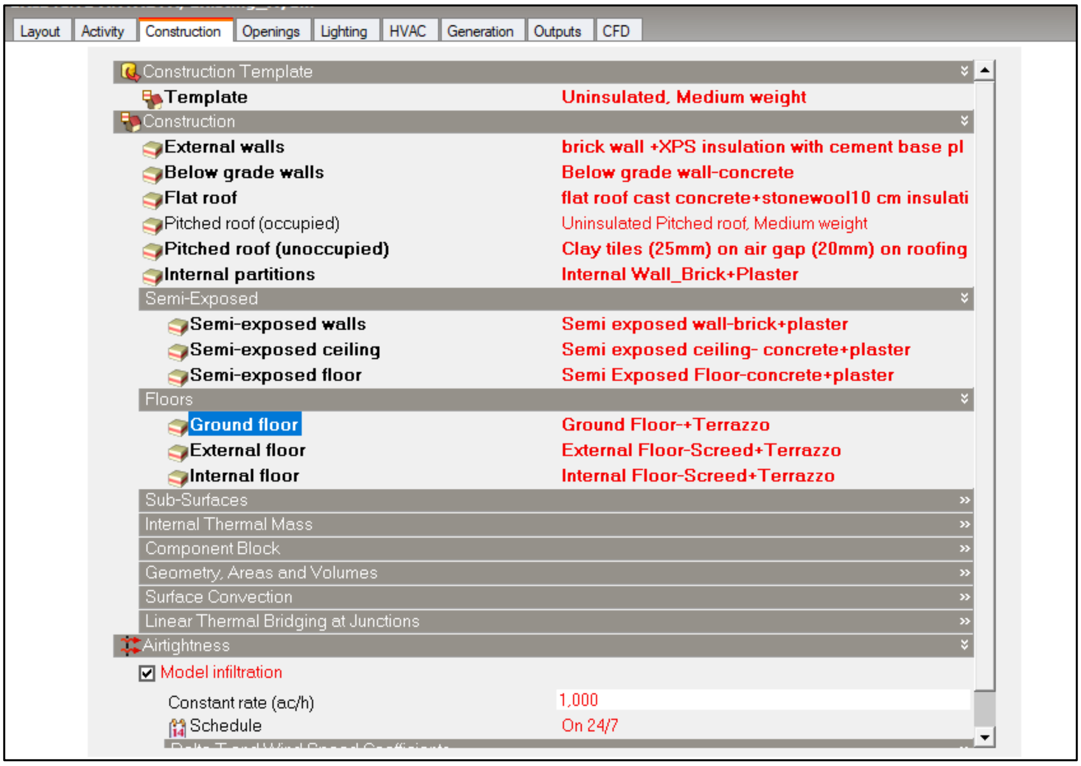

Figure A.11. Model construction data of proposed retrofit type 1

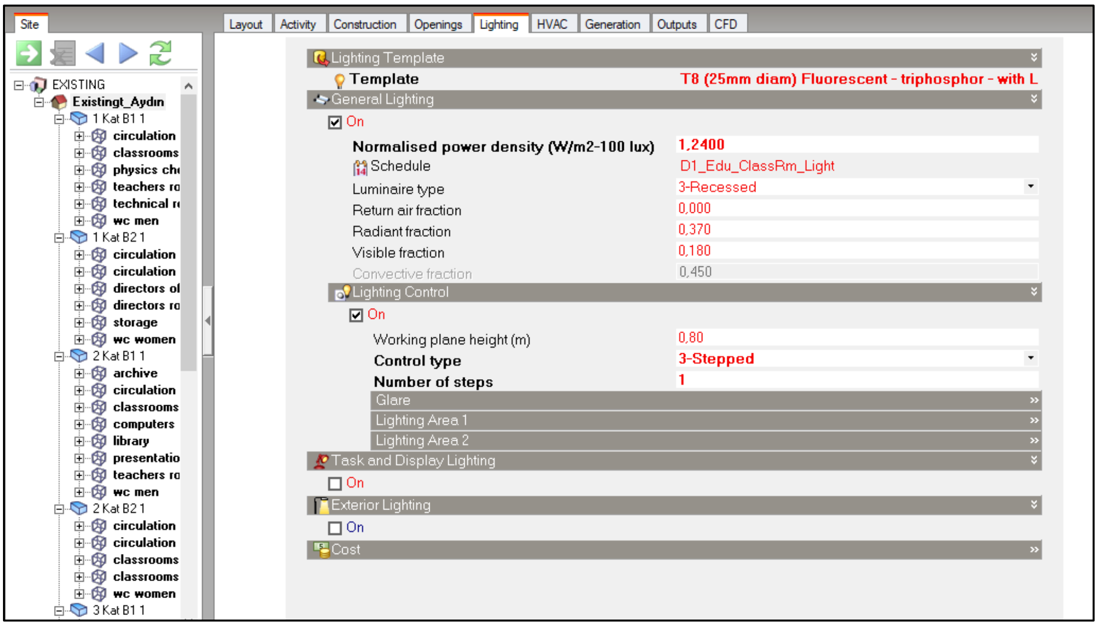

Figure A.12. Model construction data of proposed retrofit type 2

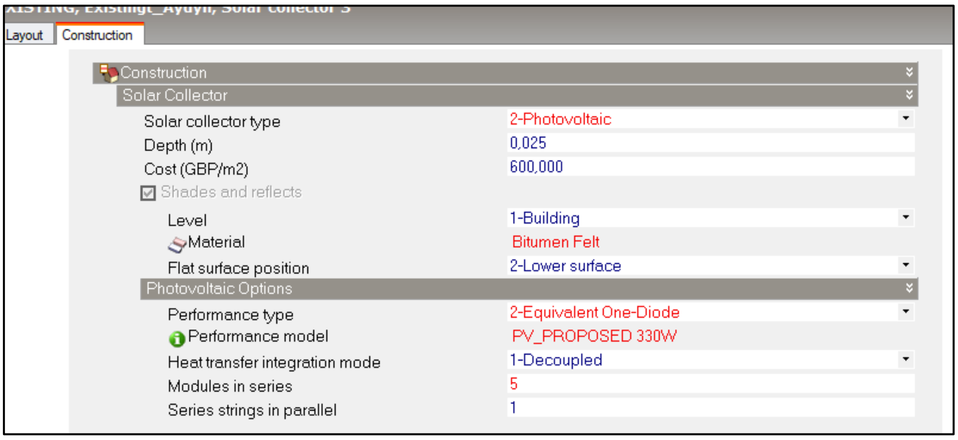

Figure A.13. Model construction data of proposed retrofit type 3

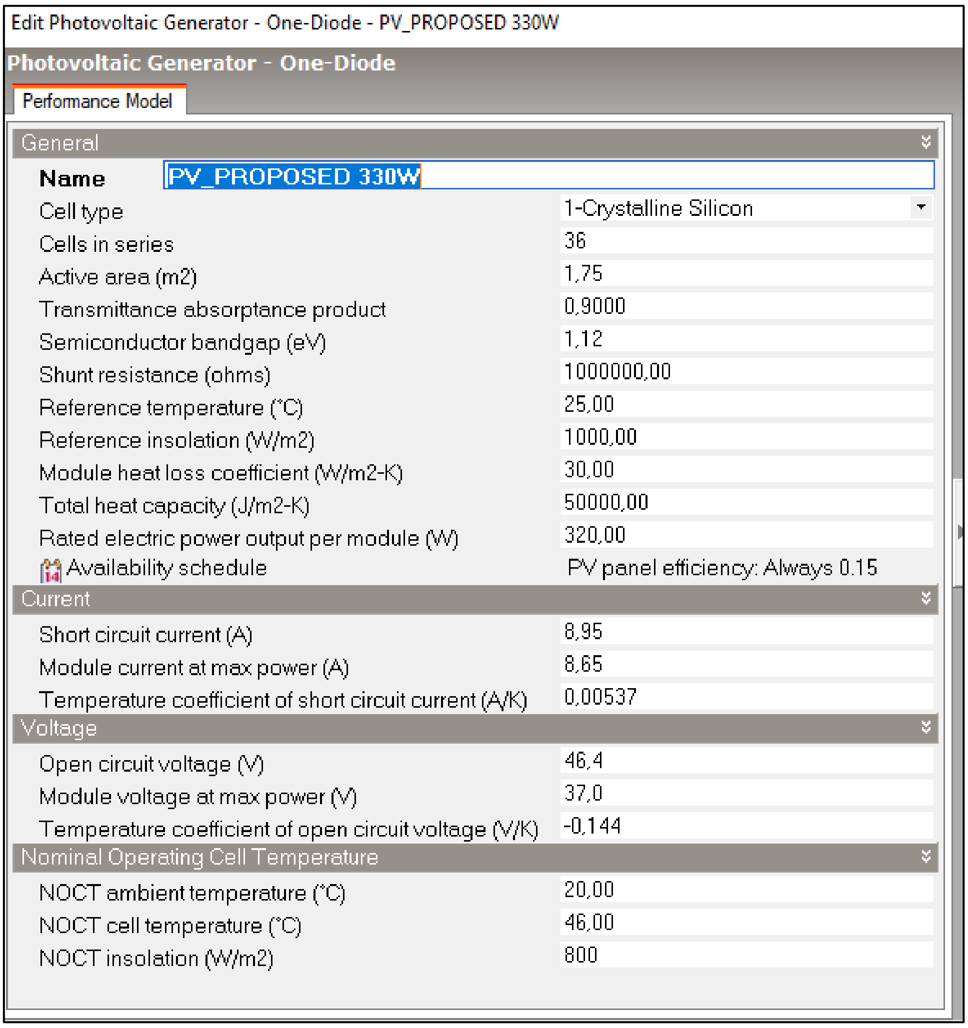

Figure A.14. Model construction data of proposed retrofit type 3

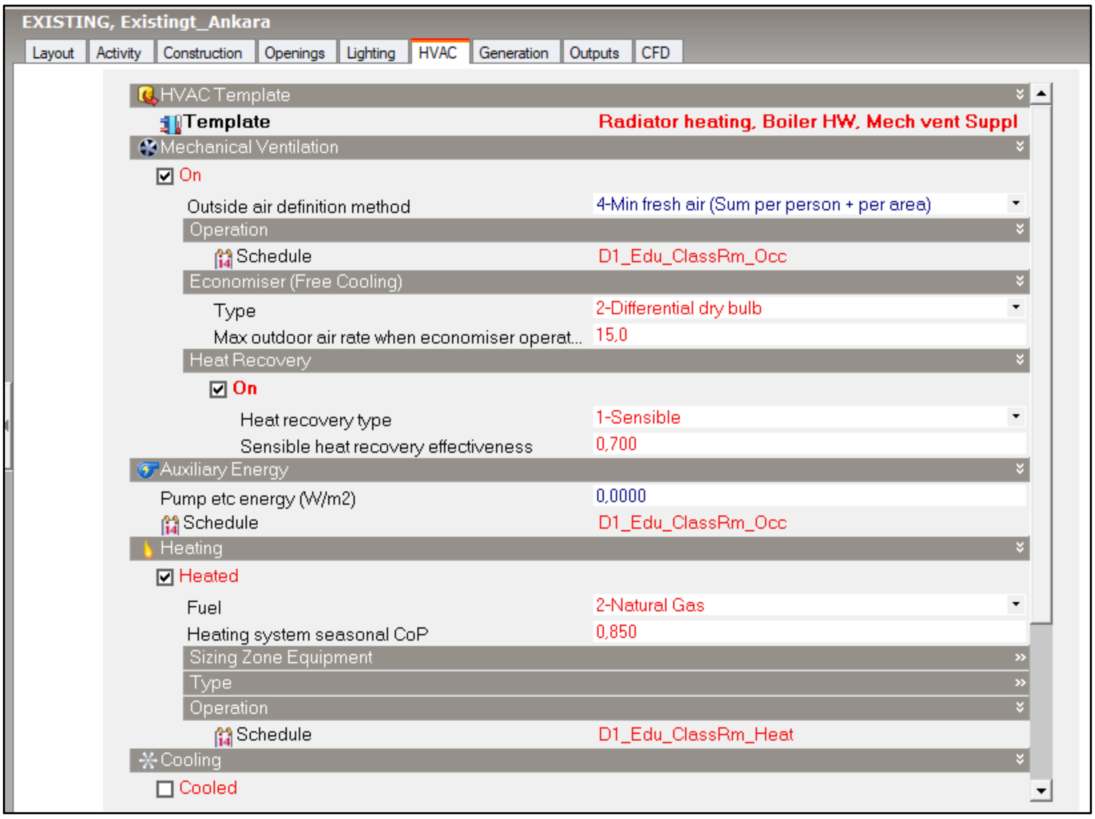

Figure A.15. Model construction data of proposed retrofit type 4

F. Sustainability Assessment Results

Table A.2. *Economic sustainability assessment results-Aydın*

AYDIN

1.RETROFIT-ENVELOPE INSULATION	kWh	TL
Aydın Annual Energy Saving	19301	10374,442

1.RETROFIT-ENVELOPE INSULATION			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	75505	10374	12,523
most likely value	95677	10374	21,209
maximum value	110806	10374	43,226

PERT Distribuiton	96071,98	10374,44
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	21,46683	
Payback Period Average(n)	21,63507	0,046221

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,084613

2.RETROFIT-LIGHTING RETROFIT	kWh	TL
Aydın Annual Energy Saving	5428	2917,593

2.RETROFIT-LIGHTING RETROFIT			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	2964	2917,593	1,082
most likely value	8436	2917,593	3,397
maximum value	11628	2917,593	5,002

PERT Distribuiton	10779,39	3000,37
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	4,552509	
Payback Period Average(n)	3,263248	0,306443

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,560979

3.RETROFIT-PV INSTALLATION	kWh	TL
Aydın Annual Energy Saving	8866	4765,546

3.RETROFIT-PV INSTALLATION			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	12250	4766	3,063
most likely value	19750	4766	5,445
maximum value	22525	4766	6,470

PERT Distribuiton	21116,84	4765,546
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	5,938702	
Payback Period Average(n)	5,165285	0,1936

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,354407

4.RETROFIT-HEAT RECOVERY	kWh	TL
Aydın Annual Energy Saving	9489	5029,043

4.RETROFIT-HEAT RECOVERY			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	487179	5029	undefined
most likely value	541310	5029	undefined
maximum value	703703	5029	undefined

PERT Distribuiton	580671,1	5029,043
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	#SAYI!	
Payback Period Average(n)	undefined	0

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	undefined

Table A.3. *Economic sustainability asssessment results-Tekirdag*

TEKİRDAĞ

1.RETROFIT-ENVELOPE INSULATION	kWh	TL
Tekirdag Annual Energy Saving	38078	20467,230

1.RETROFIT-ENVELOPE INSULATION			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	75505	20467	4,704
most likely value	95677	20467	6,375
maximum value	110806	20467	7,812

PERT Distribuiton	83519,15	20467,23

Discount Rate	0,0915

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	5,338612	
Payback Period Average(n)	6,308363	0,15852

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,26185

2.RETROFIT-LIGHTING RETROFIT	kWh	TL
Tekirdag Annual Energy Saving	5768	3100,346

2.RETROFIT-LIGHTING RETROFIT			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	2964	3100,346	1,046
most likely value	8436	3100,346	3,270
maximum value	11628	3100,346	4,801

PERT Distribuiton	8532,318	3100,346

Discount Rate	0,0915

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	3,31345	
Payback Period Average(n)	3,111597	0,321378

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,530867

3.RETROFIT-PV INSTALLATION	kWh	TL
Tekirdag Annual Energy Saving	6449	3466,389

3.RETROFIT-PV INSTALLATION			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	12250	3466	4,461
most likely value	19750	3466	8,415
maximum value	22525	3466	10,312

PERT Distribuiton	17184,1	3466,389

Discount Rate	0,0915

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	6,903247	
Payback Period Average(n)	7,96906	0,125485

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,207282

4.RETROFIT-HEAT RECOVERY	kWh	TL
Tekirdag Annual Energy Saving	20477	10852,829

4.RETROFIT-HEAT RECOVERY			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	487179	10852,829	undefined
most likely value	541310	10853	undefined
maximum value	703703	10853	undefined

PERT Distribuiton	537144,4	10852,83

Discount Rate	0,0915

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	#SAYI!	
Payback Period Average(n)	undefined	0

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	undefined

Table A.4. *Economic sustainability asssessment results-Ankara*

ANKARA

1.RETROFIT-ENVELOPE INSULATION	kWh	TL
Ankara Annual Energy Saving	66313	35643,768

1.RETROFIT-ENVELOPE INSULATION			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	75505	35644	2,461
most likely value	95677	35644	3,219
maximum value	110806	35644	3,823

PERT Distribuiton	90007,81	35643,77

Discount Rate	0,0915

$$IIC = AECS\times\left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n=-\log_{(1+d)}1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	3,000899	
Payback Period Average(n)	3,164226	0,316033

$$ECI_i=\frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,414719

2.RETROFIT-LIGHTING RETROFIT	kWh	TL
Ankara Annual Energy Saving	5504	2958,444

2.RETROFIT-LIGHTING RETROFIT			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	2964	2958,444	1,082
most likely value	8436	2958,444	3,396
maximum value	11628	2958,444	4,999

PERT Distribuiton	9707,977	3001,445

Discount Rate	0,0915

$$IIC = AECS\times\left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n=-\log_{(1+d)}1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	4,007943	
Payback Period Average(n)	3,313466	0,301799

$$ECI_i=\frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,39604

3.RETROFIT-PV INSTALLATION	kWh	TL
Ankara Annual Energy Saving	7163	3850,170

3.RETROFIT-PV INSTALLATION			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	12250	3850	3,930
most likely value	19750	3850	7,238
maximum value	22525	3850	8,753

PERT Distribuiton	18247,07	3850,17

Discount Rate	0,0915

$$IIC = AECS\times\left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n=-\log_{(1+d)}1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	6,493608	
Payback Period Average(n)	6,934323	0,14421

$$ECI_i=\frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,189242

4.RETROFIT-HEAT RECOVERY	kWh	TL
Ankara Annual Energy Saving	29128	15437,904

4.RETROFIT-HEAT RECOVERY			
Three Point Estimation	IIC	AECS	Payback P. (n)
minimum value	487179	15438	undefined
most likely value	541310	15438	undefined
maximum value	703703	15438	undefined

PERT Distribuiton	639555,7	15437,9

Discount Rate	0,0915

$$IIC = AECS\times\left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n=-\log_{(1+d)}1-\left(\frac{IIC}{AECS}\times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	#SAYI!	
Payback Period Average(n)	undefined	0

$$ECI_i=\frac{\frac{1}{n_i}}{\sum_{i=1}^{k}\frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	undefined

Table A.5. *Economic sustainability asssessment results-Erzincan*

ERZİNCAN

1.RETROFIT-ENVELOPE INSULATION	kWh	TL
Erzincan Annual Energy Saving	74975	40299,662

1.RETROFIT-ENVELOPE INSULATION			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	75505	40300	2,148
most likely value	95677	40300	2,797
maximum value	110806	40300	3,310

PERT Distribuiton	94148,56	40299,66
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	2,746883	
Payback Period Average(n)	2,774579	0,360415

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,447822

2.RETROFIT-LIGHTING RETROFIT	kV5584	TL 3001,445
Erzincan Annual Energy Saving	5584	3001,445

2.RETROFIT-LIGHTING RETROFIT			
Three Point Estimation	**IIC**	3001,445	**Payback P. (n)**
minimum value	2964	3001,445	1,082
most likely value	8436	3001,445	3,396
maximum value	11628	3001	4,999

PERT Distribuiton	8076,772	3001,445
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	3,228433	
Payback Period Average(n)	3,248504	0,307834

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,382489

3.RETROFIT-PV INSTALLATION	kWh	TL
Erzincan Annual Energy Saving	6900	3708,805

3.RETROFIT-PV INSTALLATION			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	12250	3709	4,110
most likely value	19750	3709	7,629
maximum value	22525	3709	9,266

PERT Distribuiton	20695,11	3708,805
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	8,160927	
Payback Period Average(n)	7,322351	0,136568

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	0,169688

4.RETROFIT-HEAT RECOVERY	kWh	TL
Erzincan Annual Energy Saving	34044	18043,408

4.RETROFIT-HEAT RECOVERY			
Three Point Estimation	**IIC**	**AECS**	**Payback P. (n)**
minimum value	487179	18043	undefined
most likely value	541310	18043	undefined
maximum value	703703	18043	undefined

PERT Distribuiton	566079,5	18043,41
Discount Rate	0,0915	

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d}\right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d\right) \qquad (1)$$

Payback Period Distribuiton Function(n)	#SAYI!	
Payback Period Average(n)	undefined	0

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \qquad (2)$$

Economic Impact of A Retrofit(n)	undefined

Table A.6. *Environmantal sustainability asssessment results*

AYDIN

Energy	Units	Expected Annual Energy Saving			
		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
Electricity	kWh	19301	5582	8866	9489

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2} \right)$$

		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
CO2-Eq	**kg eşd. CO2/kWh**	**15807,519**	**3449,676**	**5479,188**	**7771,294557**

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i}$$

ENI (Environmental Impact)	1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
	0,486	**0,106**	**0,169**	**0,239**

TEKIRDAG

Energy	Units	Expected Annual Energy Saving			
		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
Electricity	kWh	38078	5768	6449	20477

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2} \right)$$

		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
CO2-Eq	**kg eşd. CO2/kWh**	**31185,882**	**3564,624**	**3985,482**	**16770,69197**

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i}$$

ENI (Environmental Impact)	1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
	0,562	**0,064**	**0,072**	**0,302**

ANKARA

Energy	Units	Expected Annual Energy Saving			
		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
Electricity	kWh	66313	5584	7163	29128

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2} \right)$$

		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
CO2-Eq	**kg eşd. CO2/kWh**	**54310,347**	**3450,912**	**4426,734**	**23855,93039**

0 0

0 0

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i}$$

ENI (Environmental Impact)	1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
	0,631	**0,040**	**0,051**	**0,277**

ERZINCAN

Energy	Units	Expected Annual Energy Saving			
		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
Electricity	kWh	74975	5584	6900	34044

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2} \right)$$

		1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
CO2-Eq	**kg eşd. CO2/kWh**	**61404,525**	**3450,912**	**4264,2**	**27882,17171**

0 0

0 0

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i}$$

ENI (Environmental Impact)	1.R-Envelope Insulation	1.R-Lighting Retrofit	3.R-PV Installation	4.R-Heat Recovery
	0,633	**0,036**	**0,044**	**0,287**

Table A.7. *Social sustainability asssessment results*

	LEVEL OF IMPORTANCE			1.RETROFIT-ENVELOPE INSULATION			2.RETROFIT-LIGHTING RETROFIT			3.RETROFIT-PV INSTALLATION			4.RETROFIT-HEAT RECOVERY		
				LEVEL OF IIMPACT			LEVEL OF IIMPACT			LEVEL OF IIMPACT			LEVEL OF IIMPACT		
PARTICIPANT	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity	Health	Comfort	Productivity
T1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T2	5	5	5	3	4	4	3	3	4	4	3	3	4	4	4
T3	5	4	5	5	4	5	5	3	5	5	5	5	5	4	5
T4	5	4	4	5	4	4	5	4	4	4	4	4	5	5	5
T5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T6	5	5	5	5	3	5	5	4	5	5	5	5	5	5	5
T7	5	5	5	5	4	5	4	5	5	5	4	3	5	5	5
T8	5	4	5	3	3	4	3	4	4	4	4	4	3	4	4
T9	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T10	5	3	5	5	2	5	5	2	5	5	3	3	5	5	5
T11	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T12	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T13	5	5	5	4	4	4	3	4	5	5	3	4	5	5	5
T14	5	5	5	5	5	4	3	2	3	4	3	3	5	5	5
T15	5	5	5	5	5	4	3	4	3	4	3	3	4	5	3
T16	5	5	5	4	4	3	4	4	3	4	4	3	4	4	3
T17	5	4	5	5	5	5	5	5	4	5	5	5	5	5	5
T18	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
T19	5	3	4	3	5	4	3	5	4	5	4	1	5	4	4
T20	4	2	5	2	5	4	2	4	5	4	5	2	5	4	3
T21	5	3	5	4	4	5	4	3	5	2	3	2	5	3	5
T22	5	3	4	3	5	5	3	4	5	5	3	1	5	4	5
T23	5	2	5	4	5	4	3	5	5	4	3	2	5	3	4
T24	5	5	5	5	4	4	3	4	5	5	3	1	5	4	5
T25	5	4	5	5	4	4	3	5	4	5	3	2	5	4	5
T26	5	4	5	5	4	3	4	5	5	4	3	2	5	4	5
T27	5	5	5	4	4	4	5	5	4	5	3	1	5	4	5
T28	5	4	5	4	5	5	5	4	5	5	4	1	5	5	5
T29	5	5	5	5	4	4	3	5	4	4	3	2	5	4	5
T30	5	4	5	5	4	3	4	5	3	4	2	2	5	4	5
T31	5	4	5	4	4	4	4	5	4	5	2	1	5	5	5
TOTAL .	**154**	**132**	**152**	**137**	**134**	**135**	**124**	**133**	**138**	**141**	**117**	**95**	**150**	**138**	**145**
Total Possible Heighest Weight	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**

TOTAL.	**154**	**132**	**152**	**137**	**134**	**135**	**124**	**133**	**138**	**141**	**117**	**95**	**150**	**138**	**145**
Total Possible Heighest Weight	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**	**155**

$$RII = \frac{\sum W_1}{A \times N}$$

Relative Importance Index (RII)		
0,994	**0,852**	**0,981**

1.RETROFIT-ENVELOPE INSULATION

$$IF = \frac{\sum W_2}{A \times N}$$

Impact Factor (IF)		
0,884	**0,865**	**0,871**

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

Social Impact Index(SII)
0,823

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

Social Impact of Retrofit Type A (SOI)
0,256

2.RETROFIT-LIGHTING RETROFIT

$$IF = \frac{\sum W_2}{A \times N}$$

Impact Factor (IF)		
0,800	**0,858**	**0,890**

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

Social Impact Index(SII)
0,800

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

Social Impact of Retrofit Type B (SOI)
0,249

3.RETROFIT-PV INSTALLATION

$$IF = \frac{\sum W_2}{A \times N}$$

Impact Factor (IF)		
0,910	**0,755**	**0,613**

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

Social Impact Index(SII)
0,716

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

Social Impact of Retrofit Type C (SOI)
0,223

4.RETROFIT-HEAT RECOVERY

$$IF = \frac{\sum W_2}{A \times N}$$

Impact Factor (IF)		
0,968	**0,890**	**0,935**

$$SII = \frac{\sum_i RII_i \times IF_i}{M}$$

Social Impact Index(SII)
0,879

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i}$$

Social Impact of Retrofit Type C (SOI)
0,273